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AD-A198 527

DTRC-88/026 July 1988

Ship Hydromechanics Department  
Research and Development Report

## A Study of the Factors Influencing the Rough Water Effectiveness of Personal Flotation Devices

by

Christopher J. Hart

DTRC-88/026 A Study of the Factors Influencing the Rough Water Effectiveness  
of Personal Flotation Devices



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## REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION <b>UNCLASSIFIED</b>			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION / AVAILABILITY OF REPORT  Approved for public release; distribution is unlimited.		
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S)  DTRC-88/026			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION  David Taylor Research Center		6b. OFFICE SYMBOL (If applicable) Code 1562		7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State, and Zip Code)  Bethesda, MD 20084-5000			7b. ADDRESS (City, State, and Zip Code)		
8a. NAME OF FUNDING / SPONSORING ORGANIZATION United States Coast Guard		8b. OFFICE SYMBOL (If applicable) G-MVI-3		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and Zip Code) 2100 Second Street Washington, D.C. 20593-0001			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.
			WORK UNIT ACCESSION NO. DN505195		
11. TITLE (Include Security Classification)  A Study of the Factors Influencing the Rough Water Effectiveness of Personal Flotation Devices					
12. PERSONAL AUTHOR(S) Hart, Christopher J.					
13a. TYPE OF REPORT Final		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) 1988 July	
15. PAGE COUNT 116					
16. SUPPLEMENTARY NOTATION  (Life & Jackets)					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Personal Flotation Devices, PFD's Lifejackets		
19. ABSTRACT (Continue on reverse if necessary and identify by block number)  ➤ This report presents a study of the factors influencing the performance of personal flotation devices (lifejackets) in waves and development of methods for performing quantitative rough water experiments. This research was sponsored by the United States Coast Guard (USCG) as part of a long range scientific approach to developing personal flotation device (PFD) performance standards which insure adequate rough water flotation for the general population. Presented are results of a literature survey and background study of related research. From this study a list of significant factors are identified and organized into an overall problem definition. Experiments using a 50th percentile male anthropomorphic flotation dummy were conducted to obtain basic flotation data for comparison between several PFD's, and information on the range of PFD natural frequencies required for the design of future rough water experiments. The effects of PFD types, body weight, clothes, and joint flexibility on the natural heave periods and damping characteristics are presented, along with a limited comparison using two human test subjects. A significant finding in these tests is that the natural frequencies of all PFD's tested were within the range of waves (Continued on Reverse Side)					
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION <b>UNCLASSIFIED</b>		
22a. NAME OF RESPONSIBLE INDIVIDUAL Christopher J. Hart			22b. TELEPHONE (Include Area Code) 202-227-1554		22c. OFFICE SYMBOL Code 1562

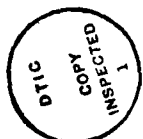
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that can be generated in a laboratory wave tank. Also, these frequencies correspond to waves generally seen in bays, lakes, large rivers; i.e. places where a heavy concentration of recreational boating activity occurs. Recommendations are given for better use of accident statistics, the acquisition of a set of anthropomorphic dummies for standardization of USCG testing, and the application of a sophisticated human body dynamics computer simulation used by the Air Force to the evaluation of PFD performance.

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## ABSTRACT

*This report presents a study of the factors influencing the performance of personal flotation devices (lifejackets) in waves and development of methods for performing quantitative rough water experiments. This research was sponsored by the United States Coast Guard (USCG) as part of a long range scientific approach to developing personal flotation device (PFD) performance standards which insure adequate rough water flotation for the general population. Presented are results of a literature survey and background study of related research. From this study a list of significant factors are identified and organized into an overall problem definition. Experiments using a 50th percentile male anthropomorphic flotation dummy were conducted to obtain basic flotation data for comparison between several PFD's, and information on the range of PFD natural frequencies required for the design of future rough water experiments. The effects of PFD types, body weight, clothes, and joint flexibility on the natural heave periods and damping characteristics are presented, along with a limited comparison using two human test subjects. A significant finding in these tests is that the natural frequencies of all PFD's tested were within the range of waves that can be generated in a laboratory wave tank. Also, these frequencies correspond to waves generally seen in bays, lakes, large rivers; i.e. places where a heavy concentration of recreational boating activity occurs. Recommendations are given for better use of accident statistics, the acquisition of a set of anthropomorphic dummies for standardization of USCG testing, and the application of a sophisticated human body dynamics computer simulation used by the Air Force to the evaluation of PFD performance.*

## ADMINISTRATIVE INFORMATION

This task was performed for the United States Coast Guard (USCG), Merchant Vessel Inspection and Documentation Division, Survival Systems Branch. The work was conducted at the David Taylor Research Center (DTRC)\* under Work Unit number 1562-600, by Code 1562, the Special Ship and Ocean Systems Dynamics Branch of the Ship Dynamics Division.

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\* Formerly the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). The name was officially changed to David Taylor Research Center (DTRC) in September, 1987.

## INTRODUCTION

Based on annual statistics, over 1000 fatalities will probably occur this year in recreational boating accidents, and in four out of five cases, a personal flotation device (PFD) will not have been utilized. Authorities believe that as many as 80% of these deaths could be prevented if the boaters were to wear PFD's. While the number of people wearing PFD's has improved significantly over the past ten years (primarily due to education and more comfortable devices on the market) less than one out of five recreational boaters are wearing their PFD's.

In 1985 the Coast Guard approved a new class of PFD called a *Hybrid*, that has a small amount of inherent buoyancy (7.5 lb), and an additional amount of inflatable buoyancy totaling at least 22 pounds. This type of device can be made much lighter and more comfortable than conventional life vests and is designed to increase the wear rate. Current regulations, however, require that the Hybrid PFD be worn while underway, in order to meet USCG carriage requirements. Since the lack of wearability is such a major problem, it is imperative that these PFD's be designed with minimum size and maximum comfort, and that safety not be seriously compromised. Therefore in the development of more comfortable, efficient, hybrid PFD's, it has become apparent that a better understanding of safe performance limits and design criteria needs to be established.

The Coast Guard has sponsored extensive research in the areas of PFD *reliability*, *wearability* and *physical effectiveness* to evaluate minimum performance standards for PFD's. Until recently, however, performance studies have been limited primarily to calm water flotation tests, and little is known about the amount of buoyancy required for adequate flotation in rough water (apart from the satisfactory experience with Type I PFD's). In order to gain insight into the hydrodynamics of PFD's in waves, tests were conducted by the USCG at DTRC in 1983 on over twenty PFD's using thirteen test subjects in waves (Girton and Wehr<sup>1</sup>). These tests provided qualitative information about the effects of a person's height, weight, build and sex, as well as the fit and function of the various types of PFD's on the rough water performance. The test results however, were found to be inconclusive from a quantitative standpoint and

questions remained about the relationship between standards met in calm water and safe operation in waves.

In trying to consider the dynamics quantitatively, the characterization of rough water performance becomes much more complicated than the static flotation performance. In dynamics problems the response of a system is dependent on the frequency of excitation (in this case wave frequency), and the worst case motions generally occur at or near the natural frequency of that system. If an analogy is made with buoys or ships, then the natural frequency is a function of shape and mass of the person and PFD, thus requiring detailed anthropomorphic data. But, unlike the ship or buoy, a person in the water wearing a PFD is a very non-rigid body, and the extent of this flexibility on motions is not known. The variations in human body characteristics, interaction with the PFD, and even mental attitude and physical abilities are extremely difficult variables to quantify.

Therefore, this project was undertaken to better define the problem, and design an approach to quantitatively evaluating PFD performance in rough water. The approach taken was *to evaluate past studies for scientific insights, and to consider existing technology in other fields that might relate to PFD's*. Also, as an initial approach, some experimental and theoretical techniques used in the study of motions of buoys and ships in waves were investigated and applied to PFD's.

Section 1 of this report presents the results of literature surveys and background investigations, along with an analysis of accident statistics, and a detailed discussion of the major variables involved. The purpose of this section is to provide a context in which to view past research, the current project, and future proposals in the study of PFD dynamics. It is by no means 'all inclusive', but rather provides a framework for presenting the findings of past investigators and the observations and concerns (opinions) of the author.

Section 2 presents the results of experiments performed using a 50th percentile anthropomorphic flotation dummy to study the calm water flotation characteristics, and the natural periods and damping factors of various types of PFD's. Calm water static flotation and oscillation tests were performed on the

50th percentile dummy with nine PFD's and one survival suit. Additionally, using one hybrid PFD, tests were conducted to determine the variability due to body weight, clothes, joint stiffness/flexibility, and body position. Limited correlation experiments were also performed using two human subjects to test the same hybrid PFD. Also presented in section 2 is a discussion of the basic theory of a heaving (vertical motion) buoy in waves and its analogy to a person wearing a PFD.

## **SECTION 1. BACKGROUND RESEARCH AND PROBLEM DEFINITION**

### **LITERATURE AND BACKGROUND SURVEY**

A list of reports on USCG sponsored PFD research was provided by the Survival Systems Branch at USCG Headquarters and copies of each were obtained through the National Technical Information Service (NTIS) and reviewed. These reports are listed as references 1 to 13 at the end of the text\*. Also, a Defense Technical Information Center (DTIC) Search was conducted by the Technical Information Center at DTRC. For a list of databases searched and key words used, refer to Appendix A. Several of the annually published USCG reports on Boating Statistics<sup>14,15</sup> (recreational boating accidents) and Statistics of Casualties<sup>16</sup> (on commercial vessel accidents) were obtained and reviewed for relevance to the rough water problem. Several government and private agencies and organizations who are experienced with either PFD's, or human body (anthropomorphic/ anthropometric) data and experimentation techniques, were contacted, and many provided significant resources and information. In addition to the list of References at the end of the report, a Bibliography section is included which lists the references used in this study by topic;

- Personal Flotation Device Studies
- Accidents: Statistics and Analysis
- Anthropomorphic Data and Statistics
- Hydrodynamics and Naval Architecture

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\* List of Abstracts for References 1 through 12 are available upon request from USCG Headquarters, DC

The complete lists of references obtained from the literature survey are on file at DTRC and are available for review, with the exception of the proprietary material in the DTIC listings.

## ACCIDENT STATISTICS

The context of the rough water effectiveness problem should be studied in light of available accident statistics. Annual recreational boating accidents are reported by the Coast Guard on Boating Accident Report forms (BAR's) for cases involving loss of life, severe injury, or significant damage to, or loss of the vessel. The Coast Guard estimates that they receive reports of nearly all accidents involving fatalities, but less than ten percent of non-fatal accidents. Commercial vessel accidents are reported in a "Statistics of Casualties" article presented annually in the USCG's *Proceedings of the Marine Safety Council*, CG-129.<sup>16</sup>

The number of registered recreational boats in the U.S. in 1985 was over 16 million as opposed to less than 100,000 commercial vessels (both inspected and un-inspected), thus there tends to be greater emphasis on the recreational boating population in PFD research. Nearly every research report on PFD effectiveness cites the lack of use of PFD's as the major problem in recreational boating fatalities. According to "Boating Statistics 1985",<sup>15</sup> the number of reported fatalities in recreational boating accidents in 1985 was 1,116 (down from the typical 1400-1500 range in the 1970's). Of the total 1116 fatalities, 954 or 85% were listed as drownings. The distribution of these fatalities by *Type of Body of Water*, and *Water Conditions* are presented in Figs. 1a and 1b respectively, and it can be seen that a significant number of fatalities occurred in non-tidal waters (over 75%) and in calm sea conditions (at least half). Figure 1c shows the distribution of fatalities by *PFD Usage*.<sup>\*</sup> The lack of PFD usage is clearly illustrated with over half of the year's total and over 80% of the known fatalities occurring without the aid

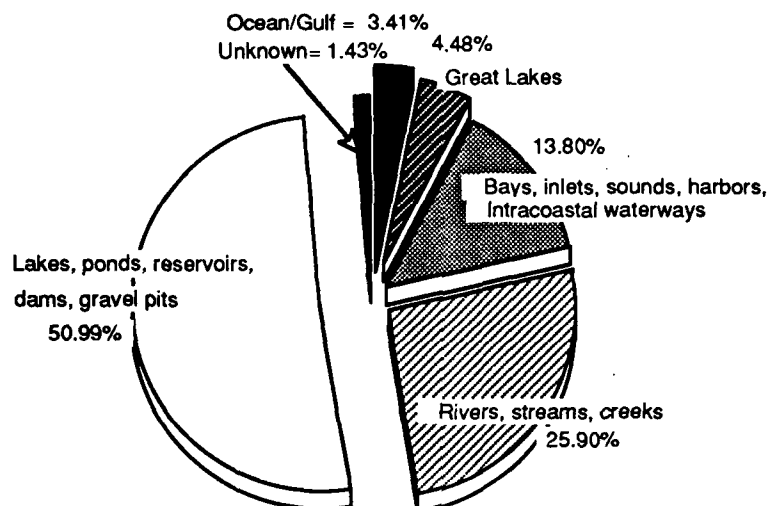
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<sup>\*</sup>It should be noted that for BAR data prior to 1987: 1) usage statistics cannot reflect whether the device was used properly or not (worn, held, etc.), and 2) "usage" statistics may be overstated due to the manner in which the data are reported. However, the BAR forms have recently been updated to reflect more accurate PFD usage data.



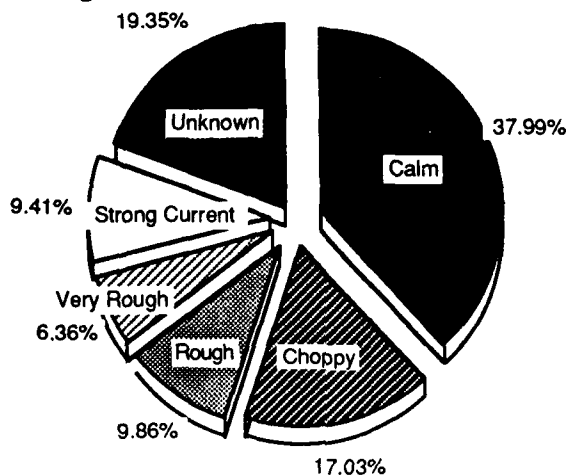
of a PFD. It can also be seen that most often PFD accessibility is not a problem. Note that 13% of the fatalities involved people who were using approved, accessible PFD's.

#### 1985 Boating Statistics; Fatalities vs. Body of Water



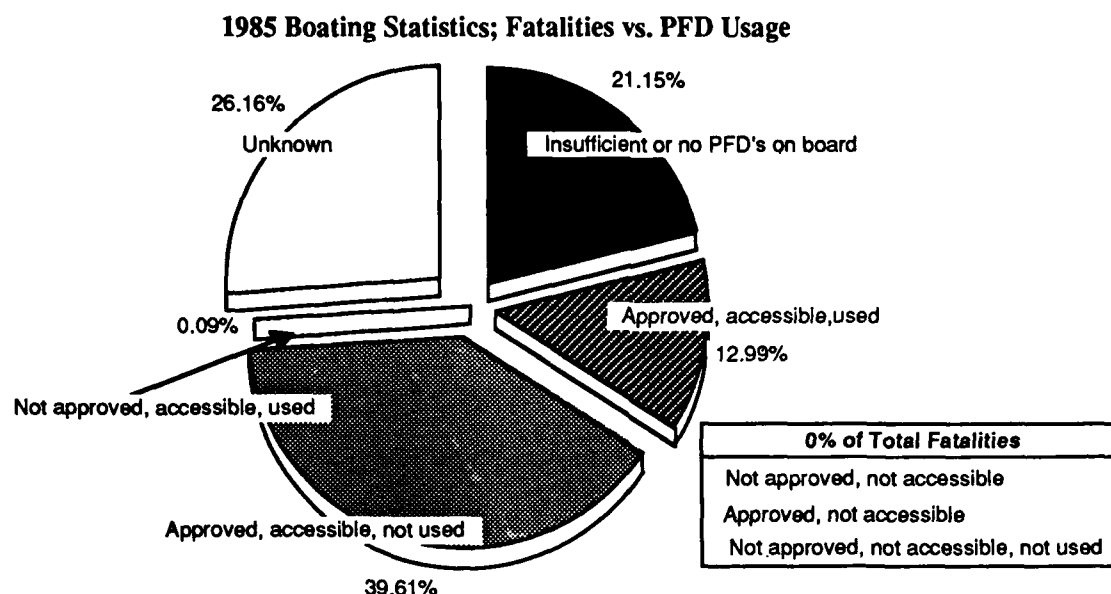
**Fig. 1a.** Distribution of recreational boating accident fatalities in 1985, as a function of the type of body of water.

#### 1985 Boating Statistics; Fatalities in Various Water Conditions



**Fig. 1b.** Distribution of recreational boating accident fatalities, as a function of the severity of the water conditions.

**Fig. 1.** Recreational boating accident fatality statistics in 1985.



**Fig. 1c.** Distribution of recreational boating accident fatalities in 1985, as a function of PFD usage, accessibility, and approval status.

**Fig. 1.** (Continued)

The question then is, "What percentage of those fatalities occurred in rough water, calm water, or were due to drowning, injury, hypothermia, etc., and how many, if any, would have been prevented by better PFD performance?" Unfortunately, there is no cross-correlation presented between the number of fatalities occurring in a PFD and the specific cause (drowning, injury, hypothermia...) or the type sea conditions (calm, rough...).

Wear rate surveys conducted by Wyle Labs<sup>6</sup> in 1975 and in 1980<sup>†</sup> confirm that less than 1 out of 5 recreational boaters wear PFD's; with that number being as low as 4% in open waters. The two surveys indicate that the overall wear rate has improved (from 7.1% in 1975 to 19.5% in 1980) and the Coast Guard attributes much of the improvement to public safety education, and the approval of Type III PFD's. In another study, Operations Research Inc.(ORI),<sup>10</sup> after sampling 245 accident reports estimated that over 90% of the drowning fatalities reviewed could have been prevented if the victim had been wearing a

<sup>†</sup> Unpublished survey conducted in 1980 by Wyle Labs for the United States Coast Guard.

PFD. The investigator was impressed with how easily people drowned, and after reviewing 50 to 100 accident reports and Coast Guard narratives gave this example as a representative type of accident:

*"A person stands up in a small boat to net a fish or change seats or start motor, etc. He loses his balance and falls overboard. He is not wearing a PFD. It is a clear calm day. He surfaces about 10 feet from the boat and is offered help by his companion who is still in the boat. He refuses, says he is OK and disappears beneath the water before reaching the boat." 10*

In a study on the involvement of cold water in recreational boating accidents, Harnett and Bijlani<sup>17</sup> present a good example of a topical analysis of the Boating Accident Reports (BAR's). They were able to make some specific conclusions on the populations at risk, and on some facts concerning cold water. Upon their review of causes of death they declared rough weather/water as a definitive cause for drownings. They cited that in some cases, regardless of PFD use and swimming skills;

*"...it is recognized that only one episode of uncontrolled breathing, associated with the stimulation of cough, swallow or sneeze reflexes, may be needed to precipitate an irreversible aspiration or ingestion of water resulting in drowning." 17*

This statement implies the need for further development of rough water PFD effectiveness while illustrating the great difficulty of such a task. Some of their findings were that:

- over half cold water related fatalities were victims who could swim but were without a PFD.
- 90% were males and half were between 15 and 35 years of age.
- 40% were in open motorboats between 12 and 16 feet in length.
- nearly three-fourths of the fatalities, for whom the time in the water is known, occur in the first 15 minutes.

This type of in-depth, topical analysis of the BAR's to identify populations at risk and various significant factors involved, serves as an example of what could be done in compiling rough water related statistics. Other references on hypothermia and cold water effects are presented in the Bibliography.

Another analysis technique which might utilize statistical data is the Life Saving Index (LSI) developed by Wyle Labs.<sup>6</sup> The LSI assigns probability indices to factors of performance such as wearability, reliability, accessibility, and physical effectiveness. The USCG currently utilizes the LSI concept for various trade-off analyses, but there are no performance indices for rough water survival at this time. It may be possible at some point to define from accident statistics a probability of survival dependent on wave conditions, ie. lower probability of survival in rougher seas. For example, a British study (Lyon and Pyman)<sup>18</sup> on casualty rates in abandoning ships at sea, while not dealing specifically with PFD's, provides interesting statistics on the marked increase of casualties occurring during the act of abandoning ship in rough seas. The casualty count includes only those fatalities involving the act of leaving the ship, not those due to the accident causing the evacuation ( fire, collision, etc.). This approach might be particularly useful in identifying general PFD performance needs in the commercial shipping area, while the BAR analysis would provide the recreational boating statistics.

Therefore, recommendations for further development in the area of statistics are as follows. Cross-correlation of the BAR data should be performed to present relationships between the number of drownings occurring with and without a PFD, as a function of various sea conditions. From this, a percentage distribution of probability of survival in calm versus rough water could be identified, and possibly added to the indices in the LSI analysis. Also recommended are further analyses of specific accident reports for specific clues to the various mechanisms involved in rough water performance. While wearability may be the issue for recreational boaters, several references cited the cold water problem and the use of survival suits to be of concern to the commercial boating industry. The USCG has already sponsored extensive research in the area of hypothermia and the use of survival suits. With regard to rough water, wave tests should be specifically designed to study performance of a survival suit in waves typically seen offshore (where survival suits are used most ), while designing experiments to test PFD's in the type of waves more often encountered in the non-tidal waters of the U.S. (where PFD's are used most).

## ELEMENTS OF THE PROBLEM DEFINITION

What are the significant factors involved in trying to evaluate the ability of a PFD to support a person in rough water? What are the measurable effects of a person's size, weight, buoyancy, swimming ability, etc. on PFD performance? Can experiments be designed to evaluate the effectiveness of different types of PFD's on different types of people, in different types of sea conditions? These are complex questions involving large numbers of variables and unknowns, requiring many assumptions and/or significantly more research. Figure 2 presents an organization of various elements of the rough water PFD dynamics problem in three major areas; *Input Scenario*, *System Dynamics* and *Performance Assessment*. This *problem definition* mainly refers to performance aspects and therefore the assumptions made with regard to wearability and reliability are that a PFD is being worn (properly) and that it is functioning as designed.

### *Input Scenario*

In the area of Input Scenario, the variability of different types of PFD's, of human factors, and of environmental factors all contribute to the formulation of the problem. Different combinations of these factors could require completely different technical approaches.

*PFD Types.* In defining the motions problem, the type of PFD being considered is significant since there are so many designs, each having different physical attributes for various specific applications.\* Physical differences between PFD's such as mass, total buoyancy, distribution of buoyancy, rigidity, etc. have a significant influence on the rough water motions. Specific quantities such as center of gravity and center of buoyancy are difficult to determine since PFD's are generally non-rigid, and irregular in shape, and conform differently to the various body sizes of wearers. Therefore, detailed data on PFD's are not readily determined as they could be for a rigid body such as a ship or buoy.

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\* A description of the five classes or 'types' of recreational use PFD's that receive USCG approval is provided in Appendix B.

# Elements of the Problem Definition for PFD Dynamic Performance Evaluation

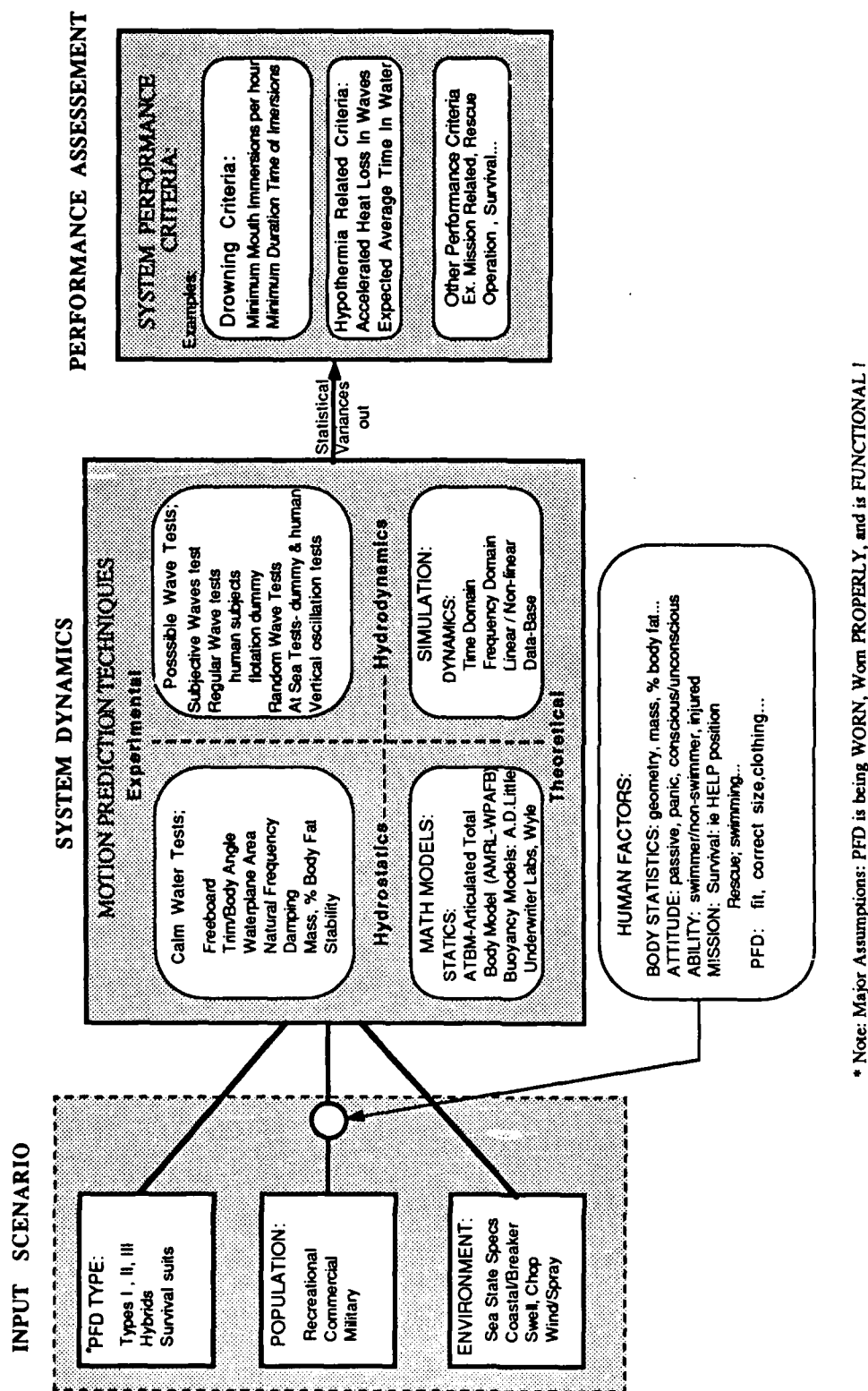


Fig. 2. Elements of the problem definition.

Techniques used to evaluate performance may vary depending on the type of PFD. For example, an extreme comparison is that of a lifejacket to a survival suit. The survival suit has characteristics more like a raft than a lifejacket, typically having much more buoyancy and a tendency to float the wearer in a more horizontal position. The performance in waves is probably much different, with the survival suit contouring the surface of most waves, while the wearer in a lifejacket will respond with a more vertical, 'spar buoy' like motion. Also, the purpose of a survival suit (thermal protection, survivability in extreme weather) may govern that the test conditions of interest be much different than for a lifejacket. Therefore, in identifying performance requirements and developing methods of testing PFD's, several technical approaches may be necessary, depending on the type of device.

*Population.* While it has been said that "no two people are alike", the engineering ramifications of that fact are staggering to anyone trying to quantify human performance. The second area under Input Scenario in Fig. 2 lists three populations of possible interest in the study of PFD performance; *Recreational* (general boating public), *Commercial* (fishermen, watermen, merchant seamen) and *Military*. The operational requirements or practical needs, as well as differences in the human factors area (also listed in Fig. 2) probably varies significantly for these three people groups. Differences in their experience at sea, physical conditioning, swimming ability, etc., may affect their minimum requirements for adequate flotation in waves.

Researchers conducting calm water PFD experiments such as described in Wyle,<sup>5</sup> and Underwriters Laboratories (UL),<sup>8</sup> have typically used ten to fifteen male and female test subjects varying in height and weight (from approximately the 5th to 95th percentile) to account for the effects of various body types. Repeatability of results using different sets of test subjects has not always been consistent and several researchers have recommended the use of anthropomorphic dummies to provide a control or a standard, in the testing process. The ability to provide some type of control element becomes even more important with regard to tests in waves since there are so many more factors involved than in the calm water case. As the PFD problem is currently understood, the type of anthropometric information needed

in addition to the readily available height and weight data, includes buoyancy distribution, mass and inertial characteristics, joint flexibility and range of limb motions.

Specific anthropomorphic data are generally available in two categories; civilian (general population) and military personnel. The National Center for Health Statistics reports on height and weight distributions for various segments of the population. Listed in references 19 to 22 are some sources of this data. The type of data found in military surveys are generally better suited for dynamics studies. NASA report 1024, *The Anthropometric Source Book* (3 volumes), is one of the most comprehensive sources of detailed human factors engineering data available. Volumes I and II<sup>23,24</sup> include detailed information on distributions of body dimensions, weights, centers of gravity, and moments of inertia as a function of body position, joint flexibility and limitations on range of motion and much more. Volume III<sup>25</sup> is an annotated bibliography of anthropometric information. Data such as this are being used in studies such as Space Shuttle applications, jet pilot ejector seat design studies, automobile crash simulations, and passenger restraint system designs. The field of human engineering is growing rapidly, utilizing statistical data, computer simulations, mannequin (dummy) testing, and human testing.

Therefore, in assessing PFD performance for various populations, it is important that differences in anthropomorphic characteristics, as well as specific data requirements be identified and narrowed down, based on the function or mission.

*Environment.* Some of the environmental factors that might govern an approach to rough water PFD performance are listed under *Input Scenario* in Fig. 2. The types of waves used to characterize a "rough water" environment are significant to PFD dynamics and should not be generalized. Open ocean seas, generally referred as *sea states* (numbered 1 through 9 depending on severity), are composed of waves of various heights and frequencies, traveling in many directions. Their properties are dependent on local and global geography, and seasonal as well as local weather patterns. Marine scientists and engineers use various statistical distributions to represent these sea states in terms of wave heights and wave frequencies. Different methods are required however, for coastal, shallow water, or breaking



waves, which are sensitive to water depth and can present more difficulties in analysis methods (non-linearities, etc.). The *Shore Protection Manual* <sup>26</sup> is a good reference on the treatment of water wave mechanics, for the various breaking and nonbreaking wave regions.

The importance of flotation assistance in a severe wave environment is graphically illustrated in a recent marine accident report by the National Transportation Safety Board<sup>27</sup> on the "*Near Capsizing of the Charter Passenger Vessel, MERRY JANE*", in February 1986. The *MERRY JANE*, a 65-foot sport fishing vessel was approaching an inlet on the California coast when it was struck and nearly capsized by a large 10- to 11-foot breaking wave, which rounded the boat broadside to the waves and swept four people overboard. The next two successive breakers washed 15 more people overboard. Of the 19 overboard, 10 were rescued, 9 drowned. At the time of this accident none of the 48 persons on board were wearing PFD's. Most of the survivors reportedly did so (survived), only by grabbing a hold of some form of flotation (2 acquired PFD's , 1 reached a lifeboat, others clung to floating debris). Survivors were rescued within 30 minutes and the report represents their account as follows;

*"As each breaker struck them, they were forced under the surface, and, in some cases, churned around by the action of the water. One survivor stated that he touched the ocean floor at least once; another stated that his ears popped due to the pressure caused by the depth of the water. The water depth at the accident location was approximately 24 feet. Most of the survivors who went overboard stated that all of their strength and endurance was required to reach the surface after being struck by breakers and to remain afloat after the breakers subsided until rescued"* <sup>27</sup>

Clearly, this type of wave action is different from what the recreational boater typically encounters, but it is interesting to note that flotation assistance of any kind has potential to save lives. This environment is also much more severe than the type of waves that could be generated in a laboratory wave tank to perform rough water experiments. However, in *Geartest Magazine*<sup>28</sup> a report of rough water PFD tests conducted in waves less than 2.5 feet high (2.25 second period) in a British ship model testing facility gave the following account of the waves;

*"... the waves were particularly short and steep to the point of breaking. So much so that the guinea pigs [human test subjects] and observers found them frightening, and the need for proper lifejackets in these cold and sinister seas was readily appreciated. ...the seas had such a debilitating effect that without full support [high buoyancy PFD], the wearer would have been overcome rapidly."*<sup>28</sup>

It should be evident from these examples that in developing performance criteria or even designing PFD experiments, the type of waves comprising "rough water" needs to be more specifically defined. Other environmental conditions that might affect the rough water survival of a person in a PFD include wind and spray, which can not currently be quantified. Separate studies would be required to investigate methods of evaluating the effects of wind and spray on survival.

### *System Dynamics*

The area of *System Dynamics* is probably the most difficult since there are a significant number of static (calm water) and dynamic (rough water) variables involved and assumptions made in predicting or characterizing motions in waves. In this area, four quadrants are used (in Fig. 2) to show possible approaches to motion prediction utilizing experimental and theoretical techniques in both hydrostatics and hydrodynamics.

*Hydrostatics.* Most of the experimental performance studies, to date have been concerned with the calm water flotation characteristics of a person wearing a PFD. The current practice for testing new PFD's is to determine the flotation characteristics of freeboard, body angle and turning time on 10 to 15 test subjects. Freeboard is the distance from mouth to water surface, body angle is the torso angle relative to water surface, and turning time is the time that it takes for a PFD to turn the wearer face up, from a face down position. Standards for freeboard, face-up stability, turning time and total PFD buoyancy must be met to receive USCG approval under the various *Type* classifications for recreational PFD's. Standards for commercial vessels transiting international waters follow the International Maritime Organization's (IMO) Safety of Life at Sea (SOLAS) requirements of 12 cm (4.7 inches) freeboard and a turning time of 5

seconds. The SOLAS requirements do not specify a PFD buoyancy requirement but in order to achieve the required freeboard, most European and commercial PFD designs tend to have relatively high buoyancies (as compared to recreational PFD types in the U.S.). The list of *calm water tests* in Fig. 2 includes standard measurements as well as some suggested additional measures which would provide information on the dynamic characteristics (mass, waterplane area, natural heave frequency and damping). These will be discussed further in Section 2 of this report.

Theoretical modeling of the calm water flotation equilibrium of a person in a PFD has been attempted by several investigators, but so far none have been able to adequately model all of the details necessary for reliable predictions. Successive attempts to apply rigid body, hydrostatic principles in theoretical modeling were done by Booz-Allen Applied Research,<sup>13</sup> A. D. Little,<sup>12</sup> UL,<sup>8</sup> and Wyle,<sup>5</sup> with each investigator adding to the previous model's level of detail. The major problems encountered in modeling were that the sensitivity of the flotation equilibrium calculations require detailed knowledge of the center of buoyancy of both the PFD and person (cited by UL<sup>8</sup> in sensitivity analysis section). Also, the buoyancy and stability characteristics vary with the emergence of various parts of the PFD and person's body at the water surface, as a function of body angle. Accounting for this would require extremely detailed geometric modeling and iterative calculations. Other problems in modeling involve the simplifying assumptions regarding the rigidity of both the PFD and person, such that the effects of various limb positions (bending arms, knees, arching back), limb stiffness, and independent movement between PFD and body, cannot be completely accounted for. In fact, these same problems are why it is difficult to obtain repeatable experimental results, and as observed by UL,<sup>8</sup>

*"variations among individual test subjects mask any relationship that might exist between emergence and equilibrium angle."*

In order to provide correlation between theory and experiment, several investigators have advocated the development and use of anthropomorphic dummies in PFD experiments. In 1969, Dr. E. McFadden<sup>29</sup> at the Civil Aeromedical Institute (CAMI), of the Federal Aviation Administration (FAA),

reported on the use of a 50th percentile anthropomorphic dummy specifically developed for PFD design tests citing that

*"...survivors' behavior in water cannot be accurately simulated by conscious subjects who are understandably unable to repress basic and subtle reflexes involving body righting actions and respiratory activity."* <sup>29</sup>

Wyle Labs<sup>5</sup> also utilized this dummy in some of their calm water PFD tests and reported that the dummy provided *"good correlation with the portion of the population that it was built to represent"* and further recommended that a set of dummies be built to model a range of body sizes such as the 5th, 50th and 95th percentiles.

Another possibility for theoretical modeling involves the potential utilization of an existing state of the art human body dynamics computer simulation. This simulation, referred to as the *Articulated Total Body Model (ATB)* was originally designed for use in automobile crash simulation and has been developed by the Air Force Aerospace Medical Research Laboratory (AFAMRL) to perform biodynamic simulations of interest to the Air Force, such as pilot-ejector seat flight simulation. The ATB Model is described by Kaleps and Marcus<sup>30</sup> as follows,

*"The model structure is based on rigid body dynamics which assumes that body segmental masses and moments remain constant during body motion. The segments are coupled at joints which allow deformation and application of torques as functions of joint orientation and rate of change of that orientation. External forces can be applied to body segments in the form of contact forces and/or pressures acting on an ellipsoidal approximating surface for each segment, or as whole body forces, such as gravity. Contact forces can also be applied between body segments. Also, forces can be applied by means of restraint system interactions and defined motion constraints on or between body segments."*

*The basic formulation of the ATB Model is quite general and can be used as an analytic tool for the numerical solution of highly complex dynamic systems*

*which can be couched in terms of a multiple rigid body system description. The specific use of the ATB Model for the prediction of human body dynamics merely depends on the incorporation of an appropriate data set for the geometrical, inertial and material properties of the human body."*

Based on discussions with AFAMRL experts, the ATB Model may have several potential applications in PFD research.

*Hydrodynamics.* In the area of hydrodynamics, there are many possible approaches to PFD performance in waves, utilizing both experimental and theoretical techniques (Fig. 2), depending on the type of waves and specific objectives of study. Because of the complexity of the hydrodynamics (particularly as applied to humans), no single type of test or calculation can be performed to evaluate the overall *rough water* performance of PFD's. The large number of variables (from various characteristics of PFD's populations and environment), the many degrees of freedom, and the lack of boundary conditions suggest a nearly impossible problem, from a purely *quantitative* stand point. However a reasonable objective might be to identify the most critical factors involved in PFD designs by utilizing qualitative means of testing to answer questions on *what* happens in rough water. Then, specific types of quantitative means might be used to pinpoint *why* the observed behavior occurs.

Several researchers have conducted *qualitative* or *subjective* studies in ship model type wave tanks using human subjects to evaluate the adequacy of the current calm water PFD performance standards in a (simulated) rough water environment. Four major experiments of this type; conducted by the USCG (Girton and Wehr<sup>1</sup>), Geartest Ltd.,<sup>28</sup> Robert Gordon Institute of Technology,<sup>32</sup> (RGIT), and Wyle Labs\* are presented and discussed in more detail in section 2. These experiments have provided important information on several aspects of rough water performance, such as: evaluations of PFD fit and comfort, effectiveness of straps and attachment designs, requirements for head support, minimum comfortable

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\* Wyle Laboratories, "Rough Water PFD Test Letter Report," United States Coast Guard, Sponsor, Contract DOT-CG-831476-A, unpublished.

buoyancy, ease of inflation of hybrid PFD's, and ability to perform maneuvers in waves. However, each of the experiments were conducted in a limited number of wave frequencies, and because the motion responses are strongly dependent on wave frequency, some conclusions may be misleading. Particularly if the wave frequencies were near the natural frequencies of *some* of the device/person combinations, but not of others. Another limitation in these subjective type tests is again the variation in test subjects' ability to perform repeatable experiments. Here, as in the calm water experiments, the investigation of use of dummies as a control has been recommended by many.

In Fig. 2, several types of experiments are listed in addition to subjective experiments. These are based on an analogy to a rigid body or ship dynamics approach. Quantitative experiments might be possible in these areas to investigate specific aspects of rough water performance, and even to evaluate whether behavior of a person in a PFD has any similarity to rigid body or not. Section 2 of this report presents experiments specifically aimed at investigating that analogy in a basic way by using an anthropomorphic dummy to study the vertical plane (heave) natural frequencies of oscillation. Other test types used to study motion response quantitatively, include experiments conducted in regular sinusoidal waves; random waves (modeling the environment), and forced oscillation experiments (to obtain detailed hydrodynamic information).

In the design of wave experiments, the specific wave site or type of facility to be used also depends on the degree of severity of the desired wave conditions. Ship model wave tanks are designed to study regular and random waves at a significantly reduced model scale ratio. These facilities are therefore generally limited in their ability to generate full scale seas\* (with proper frequency content). Theme park wave pools typically generate *regular*, shallow water (possibly breaking) waves. Full-scale testing would require a location with good accessibility, much safety planning, and cooperation from the weather. In any kind of wave test, the method of instrumenting a person for motions is difficult (small, light

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\* The Oregon State University has an outdoor wave making Facility that can reportedly generate a full scale sea state 3.

weight/neutrally buoyant, waterproof package, telemetry, etc.). The problem of instrumentation is somewhat easier on a mannequin, and facilities such as AFAMRL ought to be further consulted.

Theoretical approaches, should also be considered to study and identify the driving, or significant factors in motion response. Time domain and frequency domain simulations are used in marine hydrodynamics. An example of a relevant time domain prediction program is presented by Nath and Hudspeth,<sup>33</sup> on the motions of a drifting buoy, in waves. More typical in ship design is the use of frequency domain programs which allow evaluation of motion response in multiple frequency wave environments. While these programs (based on years of development) apply the state of the art in computations of hydrodynamic forces and motions of a rigid body in waves, none are applicable to a geometry as complex and flexible as a person in a PFD. On the other hand, some of the detailed capabilities in a program such as the ATB model described previously might have applications, particularly in the area of flotation equilibrium calculations. While the ATB model currently has no hydrodynamic capabilities, the modeling aspects of the body in motion are already well defined. The capabilities of hydrodynamicists to model the wave environment, hydrodynamic forces, and motion response; and of biodynamic experts to model human dynamic behavior, have not previously been jointly applied. Development of this joint capability is recommended.

### *Performance Assessment*

The area of *Performance Assessment* involves the identification of performance criteria for evaluation purposes. Even if the exact motions of a given body in waves were known or could be predicted, what quantitative measures would define acceptable performance? For example: "How many wave impacts to the face per hour are tolerable without having a high probability of drowning"? Here, the services of a physiologist might be utilized to study the effects of the frequency and duration of mouth immersions on human survival. In other words, what are the quantitative relationships between motions caused by waves, and resulting effects on the wearer's survival? Hypothermia studies, for example have been conducted on human test subjects to record heat loss in waves in order to correlate water roughness

with the acceleration of hypothermia. The decrease in the probable survival time due to wave motions is reported by Steinman<sup>34</sup> for several types of lifesaving gear and might be useful in developing a hypothermia performance requirement or criteria. Other performance criteria might be determined based on surveys or testing related to specific PFD applications.

## RESULTS IN SECTION 1

It should be evident at this point that the evaluation of rough water performance of PFD's is a complex problem that encompasses many areas, and that there needs to be significantly more research. While much information can and should be utilized from advanced technologies (such as aerospace and automotive) it should also be noted that there are less resources available for PFD research since there are significantly fewer lives involved. In light of this limitation, Fig. 3 presents possible objectives ranging from the near to long term as a framework for setting priorities in PFD research and development. It is further suggested that research and development being conducted to meet specific near or short term goals be conducted in such a way as to provide data for intermediate and long term interests as well (ie. having the strategy of obtaining short term results while gaining long term capabilities). For example, the acquisition of an anthropomorphic flotation dummy or set of dummies could have applications in all three areas. In the short term, a dummy could be used in practical tests where human subjects wouldn't be safe such as; tests in severe waves, tests requiring a long time in the water, and drop/jump tests (of PFD durability) from high elevation. In the intermediate term the use of the dummy as a test subject in routine PFD approval tests would provide quantitative data for comparison between PFD's, as well as experience with the dummy which might lead to more repeatable, more cost effective testing practices. And long term, the dummy results would be useful in the development and verification of theoretical prediction models (both static and dynamic). This might lead to the identification and evaluation of quantitative parameters or characteristics that can be associated with rough water performance.



# PFD HYDRODYNAMIC PERFORMANCE R & D MAIN AREAS

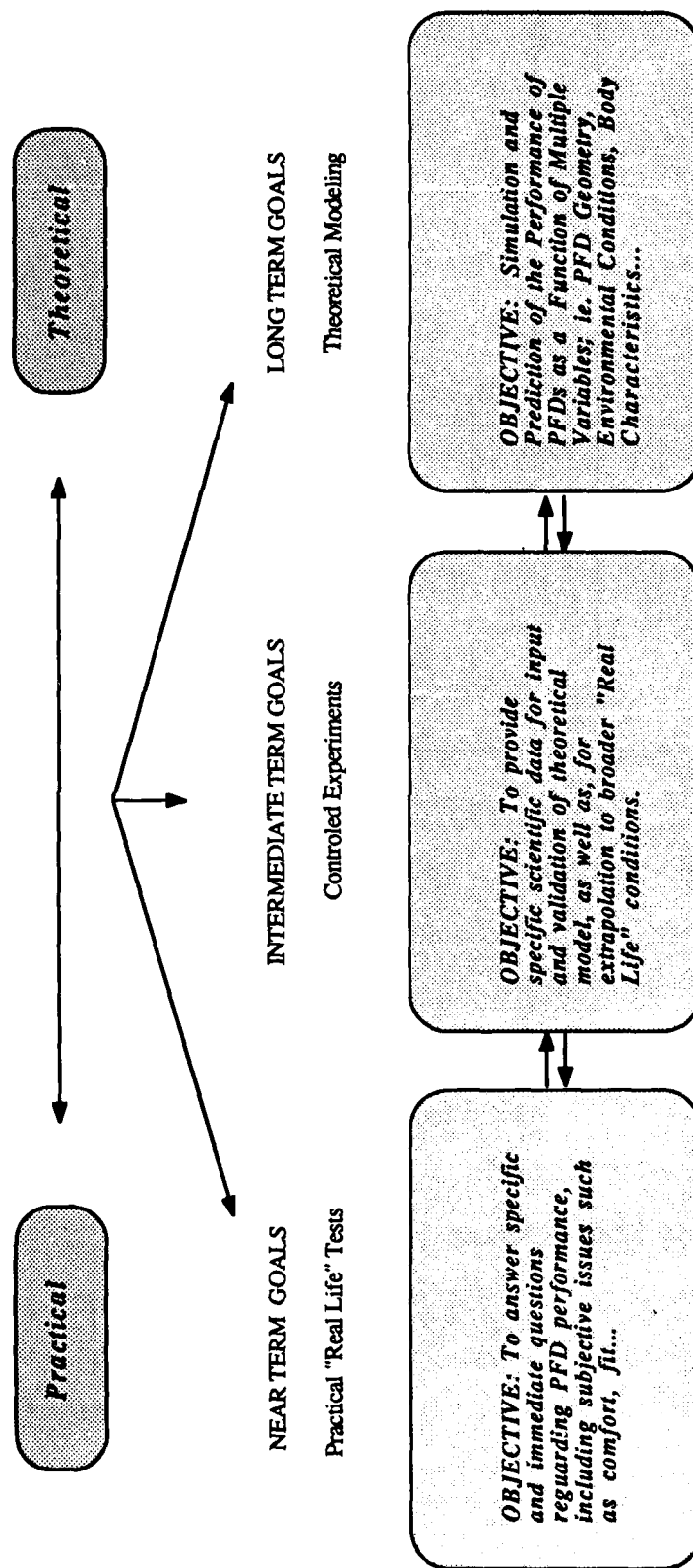


Fig. 3. Suggested main objectives in PFD research and development.

Analysis of accident statistics is another area of research that would provide information useful in meeting near to long term objectives. The near term usefulness of better accident statistics would be to identify the immediate needs and shortcomings in PFD performance (e.g., lack of use, use in calm vs. rough water, fatality rate for people wearing PFD's as a function of severity of water conditions etc.). In the intermediate term, accident data could be used to define the priorities for both quantitative and qualitative experimental test conditions. For example, if statistics showed that nearly all of the 13% of fatalities listed for persons wearing an approved PFD, occurred in ocean surf vs. calm water (or vice versa), this would impact the priorities and direction for the next phase of research (type of waves in future experiments, etc.). Long term, the statistical information might be used in the development of rough water performance indices for the LSI.

In the field of anthropometry and biodynamics it was found that a wealth of information and experience exists in other technologies, and that resources available at facilities such as AFAMRL could be utilized. It is interesting to note the parallels in transportation safety, where it has been proven that seat belts save lives, yet many people still don't wear them. Transportation safety researchers have utilized accident statistics, conducted crash testing with anthropomorphic dummies, compiled detailed databases of anthropometric information, and have developed detailed theoretical simulations in order to evaluate the reliability, wearability and effectiveness of various belt designs. Some of the visible results have been in: improved safety belt designs, legislation requiring the use of safety belts, and the development of passive restraint systems. The available anthropometric databases for various populations could be used to specify the range of characteristics that should be considered in the selection of human test subjects , and the design of a set of dummies for PFD research. The test equipment used to measure and describe the geometry of human subjects and manikins could also be used to perform the detailed measurements of PFD geometries. The ATB Model could possibly be used to perform quasi-static flotation simulations for various PFD types on various body types, to investigate the effects of location and amount of buoyancy on freeboard and turning moment, as well as to calculate the effects of body position and limb movement on

moments of inertia and centers of mass and buoyancy. The ATB Model might also provide useful calculations of parameters that are difficult to determine experimentally due to the sensitivity of the PFD/body orientation at the free surface to slight movement, or forces. Such parameters might include: waterplane area, and the above and below water volumes of the PFD (to calculate the *reserve buoyancy* of the PFD).

After performing the investigations presented in Section 1 of this report, the use of a dummy appeared to be of foremost importance in establishing any quantitative basis in experimental performance evaluation of PFD's. Therefore, the Sierra ("Sam") Anthropomorphic Flotation dummy used in tests conducted by Wyle Labs and CAMI, was obtained and refurbished for use in the experiments presented in section 2.

## SECTION 2. DYNAMIC RESPONSE EXPERIMENTS

### OBJECTIVE

Experiments were performed using a 50th percentile male anthropomorphic flotation dummy to evaluate nine PFD's and one survival suit for static flotation characteristics and natural periods of oscillation in calm water. The objective of these tests was to determine the range of variability of the natural periods and damping characteristics so that meaningful wave frequencies could be chosen in future waves experiments. The effects on natural frequency response of various PFD types, and variations in the dummy's body characteristics were investigated, and some limited comparisons were made with two human test subjects. Other objectives were (1) to see if measured oscillations correspond to linear theory of a heaving buoy when approximated using standard naval architecture calculations and (2) to evaluate the use of a dummy in experiments representing human characteristics, while providing a constant basis for performance comparison between PFD's.

## BACKGROUND THEORY

An analogy is presented in this section between the motions of a person wearing a PFD in waves and the standard treatment of the vertical motion of a ship or buoy in waves. In this analogy, several assumptions are made. A person in a PFD is assumed to be rigid enough in the vertical direction to utilize rigid body motion theory. Also, for the purpose of this project, the vertical motion, referred to as *heave*, is considered to be the primary mode of motion and uncoupled from other modes. The actual wave induced forces on a body would produce six degrees of freedom motions with coupling occurring between several modes of motion (usually some coupling between heave and pitch is expected). For a detailed presentation on the dynamics of floating bodies refer to *Principles of Naval Architecture*, (Comstock<sup>35</sup>) which is a classic text, and references; *Ocean Engineering Wave Mechanics*, (McCormick<sup>36</sup>), and *Buoy Engineering*, (Berteaux<sup>37</sup>), all of which were used in developing the following.

### *Equation of Motion*

The vertical motion of a buoy is generally treated in the same manner as a single degree of freedom harmonic oscillator. The equation of motion, from Newton's Second Law of mechanics in the vertical or z-direction can be expressed as

$$(m+a) \ddot{z} + b \dot{z} + c z = F(t), \quad (1)$$

where

$\ddot{z}$ ,  $\dot{z}$  are the first and second derivatives of heave ( $z$ ), respectively

$F(t)$  is the wave induced excitation force

$m$  is the mass of the body

$a$  is the *added mass* coefficient, due to the mass of entrained water accelerated by motion of the body

Note: the quantity  $(m+a)$  is referred to as *virtual mass*

$b$  is the *damping coefficient*, primarily due to energy dissipated in wave making and viscous effects

$c$  is the *restoration coefficient*

The restoration coefficient,  $c$ , is defined as

$$c = g \rho A_{wp} \quad (2)$$

where

$\rho$  is water density

$g$  is gravitational acceleration

$A_{wp}$  is the *waterplane area* defined as the cross-sectional area of the body at the water surface.

The natural frequency and damping characteristics are expressed essentially the same as in any basic mechanical vibrations text, such as Vierck,<sup>38</sup> except for the addition of an added mass term. The *undamped natural frequency*,  $\omega$ , in radians per second is,

$$\omega_n = \sqrt{\frac{c}{(m+a)}} \quad (3)$$

The *damping factor*,  $\zeta$ , sometimes referred to as *damping ratio*, is the ratio of damping,  $b$ , to the *critical damping*,  $b_c$ , such that,

$$\zeta = \frac{b}{b_c} \quad , \text{ and} \quad (4)$$

$$b_c = 2\sqrt{c(m+a)} \quad (5)$$

### *Free Oscillations*

Natural frequency, and added mass, and damping coefficients can be determined from free oscillation experiments in calm water. The rate of decay of motion in a damped system is approximately exponential and can be determined from the ratio of successive amplitudes. The *logarithmic decrement*,  $\delta$ , a commonly used measure of decay, is defined as the natural logarithm of the ratio of amplitudes  $n$  cycles apart, such that,

$$\delta = \frac{1}{n} \ln \left[ \frac{z_i}{z_{i+n}} \right] \quad (6)$$

where  $z_{i+n}$  is the amplitude  $n$  cycles after  $z_i$ . The logarithmic decrement is related to the damping factor by

$$\delta = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}} \quad (7)$$

and thus for small damping, the damping ratio,  $\zeta$ , can be determined from

$$\delta \approx 2\pi\zeta \quad (8)$$

$$\zeta = \frac{\delta}{2\pi} \quad (9)$$

Since the *damped natural frequency*,  $\omega_d$ , is measured in the free oscillation, and is defined as,

$$\omega_d = \omega_n \sqrt{1-\zeta^2} \quad (10)$$

the undamped natural frequency,  $\omega_n$ , can then be calculated from Eq. 10.

At this point, all the information necessary to compute the hydrodynamic coefficients  $a$ ,  $b$ , and  $c$  has been determined. The added mass can be calculated from Eq. 3, the damping coefficient from Eq. 4, and the restoration coefficient from Eq. 2 (provided the waterplane area is measured). Therefore, from the measured values of  $A_{wp}$ , and  $\omega_d$ , and the calculated values of  $\delta$ ,  $\zeta$ , and  $\omega_n$ , the hydrodynamic coefficients can be determined and used to study the motions in sinusoidal waves.

### *Forced Oscillations*

In characterizing the dynamic response of a system, it is important to consider the manner in which motion amplitudes vary with wave frequency. From the particular or *steady state* solution of equation 1, a *magnification factor* is derived for this purpose, and defined as

$$MF = \frac{Z_o}{F_o/c} = \frac{1}{\sqrt{[1-(\omega/\omega_n)^2]^2 + [2\zeta\omega/\omega_n]^2}} \quad (11)$$

where  $Z_o$  is the steady *heave amplitude*, normalized by the *static displacement*,  $F_o/c$ , and  $F_o$  is the wave excitation force amplitude. The amplitude response can then be observed as a function of the *frequency ratio*  $\omega/\omega_n$ . Figure 4 shows a sample plot of magnification factor versus frequency ratio for a range of damping factors. Note that the magnification factor is greatly attenuated with an increase in damping factor, while the peak responses occur at or near the natural frequency.

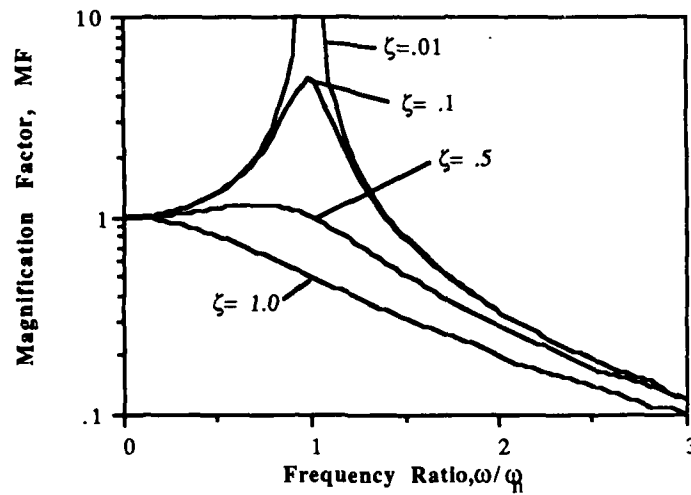


Fig. 4. Sample magnification factor for uncoupled heave.

Similarly, the phase angle,  $\sigma$ , between motion and the wave excitation force is given by,

$$\sigma = \tan^{-1} \left[ \frac{2\zeta\omega/\omega_n}{1-(\omega/\omega_n)^2} \right] \quad (12)$$

Fig. 5 shows a sample plot of phase angle versus frequency ratio for a range of damping factors. From these types of plots, the effects of mass, added mass, damping, and restoration on the heave amplitude, phase angle and natural frequency, can be compared between devices.

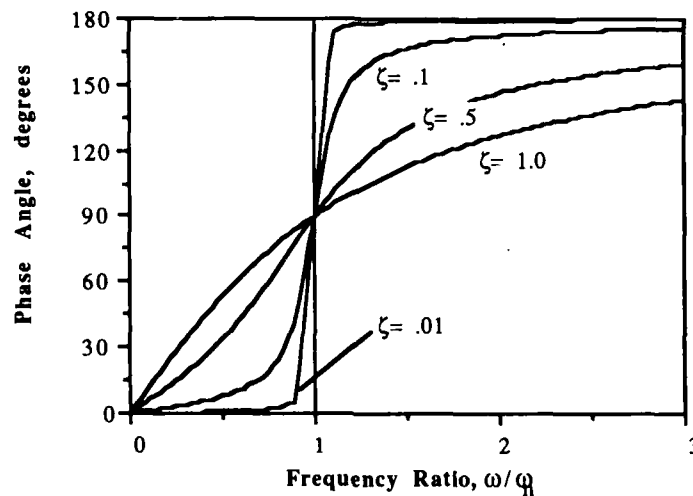


Fig. 5. Sample phase angle for uncoupled heave.

#### *Wave and Depth Effects on Magnification and Phase*

While the above approach provides a basis of comparison between floating bodies of different types, the magnitudes of motion predicted may not be representative, since it does not include the hydrodynamic effects of wave excitation forces on the body. The actual forces applied to the body by wave action are a function of several factors including: wave frequency, the added mass, damping, and restoration coefficients, the shape of the body, and the depth of the body extending below the surface. These effects are best studied using a combination of experimental and theoretical techniques.

Berteaux<sup>37</sup> presents a simplified *relative motion approach* to single degree of freedom heave, which includes the effects of the exponential decay of water particle motion in waves as a function of



depth. A magnification factor is presented that is defined as the ratio of the heave amplitude to wave amplitude, and includes a variable,  $D$ , for draft.

$$MF' = \frac{x}{r} = \frac{e^{-kD}}{m_v} \frac{\sqrt{(c - a \omega^2)^2 + (b \omega)^2}}{\sqrt{(\omega_n^2 - \omega^2)^2 + (4 n^2 \omega^2)}} \quad (13)$$

where  $x$  is heave amplitude  
 $r$  is wave amplitude  
 $k$  is wave number, defined as  $\omega^2/g$  in deep water waves.  
 $D$  is draft  
 $m_v$  is virtual mass or  $(m+a)$   
 $n$  is defined as  $b/(2m_v)$ .

Draft as defined in Ref. 37 would be the distance from water surface to the bottom or *deepest* part of the buoy, however, naval architects have used the depth to the vertical *center of buoyancy* in applying the relative motion approach with better results on ship designs (or non-flat bottom hull forms). The magnification factor,  $x/r$ , in Eq. 13 should provide an improved prediction of the motion amplitudes of the PFD/body system. The magnitude of  $x/r$  is generally lower than the magnification factor calculated in Eq. 11, and the peaks of both (Eq. 11 and Eq. 13) occur near the natural frequency (at resonance). This expression of the magnification factor as a ratio of heave to wave amplitude (Eq. 13) is analogous to what is commonly referred to as the heave *transfer function*. Also introduced in Ref. 37 is the corresponding phase angle,  $\sigma'$ , which is the phase difference between the heave motion and the wave. It is expressed as the sum of the phase angle between heave motion and exciting force,  $\sigma$  (Eq. 12.), and of the phase angle,  $\alpha$  (Eq. 14.) between the wave motion and exciting force.

$$\alpha = \text{Tan}^{-1} \left[ \frac{-b \omega}{c - a \omega^2} \right] \quad (14)$$

and total phase  $\sigma'$ , is given by

$$\sigma' = \sigma + \alpha \quad (15)$$

Some of the experimental data presented in later sections will be analyzed using Berteaux's relative motion equations, to check for the significance of body *draft* on the magnification factors and phase angles.

### *Summary*

By way of perspective, it should be noted that these techniques are presented as an approach to gain a relative understanding of the factors that influence motions, and particularly to identify the range of natural frequencies, for different types of PFD's and human body sizes. In ship dynamics (dealing with rigid bodies and less assumptions), designers use several combinations of experimental methods and analytical tools to provide motion computations on the full set of six degree of freedom, coupled systems of equations. Theoretical simulations are based on years of development including much experimental verification. Model experiments are generally conducted in three areas. *Forced oscillation* tests are conducted to determine added mass and damping coefficients in calm water by oscillating a captive model through a range of discrete frequencies and measuring the forced response. *Regular wave* model experiments are conducted in sinusoidal waves over a range of frequencies, one at a time, to determine the exact response of a ship to a specific frequency. Also, wave experiments are conducted in *random waves* to investigate the motion response in a mixed frequency wave field that is statistically representative of the expected operating environment. Free oscillation tests (such as those performed in this project) are routinely conducted as part of regular and random wave ship model experiments, to identify natural periods and damping characteristics in calm water. The approach presented in this section to observing the uncoupled heave motion response represents a classical dynamics "first cut" approach to a complex problem, and should provide a starting point and reference for further investigations.

## DESCRIPTION OF PFD'S AND ANTHROPOMORPHIC DUMMY

### *Description of PFD's*

Nine PFD's and one exposure suit were provided by the United States Coast Guard for these experiments. The USCG approves PFD's under five categories, referred to as Type I through Type V, depending on the intended use, type of vessel and attributes of the device. For a detailed description of Types I through V, see Appendix B. Each of the 10 devices tested in these experiments was given a letter designation A through J as shown in Fig. 6. PFD's A through D are *inherently* buoyant devices, while PFD's E through G are called *hybrids*, since they contain partial inherent buoyancy with additional buoyancy provided by inflatable chambers. PFD A, the Gladding '77 and PFD B, the Crawford Kapok Type II, are representative of Type I and Type II PFD's and have been used in many of the previous USCG research projects. The Reference Vest for Hybrids, PFD C, is used by the Coast Guard as a benchmark of minimum performance for USCG approval of Hybrid PFD's. PFD D, the Perry Jetfoil Type V, was included in the experiment because of its unique shape and higher buoyancy. PFD's E and F are prototype hybrids which have also been used in previous USCG research. PFD G, The Hybrid Helmsman/ERO, was the only Coast Guard approved hybrid PFD currently available on the retail market at the time of the experiment. PFD's H and I are 100% inflatables manufactured by Sonoform and are prototypes for use in commercial and military applications, respectively. The Mustang exposure suit, designated PFD J, is a commercially available survival suit and has an additional inflatable buoyancy chamber behind the head.

### *Description of Anthropomorphic Dummy*

The anthropomorphic flotation dummy used in these experiments was obtained from the Civil Aeromedical Institute (CAMI) of the Federal Aviation Administration (FAA), in Oklahoma City, Oklahoma. It was constructed in 1965 by Sierra Engineering to represent a 50th percentile male. Consisting of 14 major sections, each section was built to model the human mass and buoyancy

distribution, as well as joint rotation limits, providing realistic body postures and motions. Details of the dummy, as constructed, are given in Refs. 39 and 40. Designated as "*Sierra Sam*", this dummy has been used in PFD tests by the FAA/CAMI <sup>29</sup> and by Wyle Labs,<sup>8</sup> and while it is over 20 years old it was the only *flotation capable* anthropomorphic dummy of this level of detail, that could be located for use in these tests.

The basic dummy characteristics, as tested, are given in Table 1. The 50th percentile dummy was ballasted to only 155 lb rather than the original design weight (162 lb), in order to correspond to Wyle Labs' PFD tests using *Sierra Sam*. The buoyancy of each segment was modeled after the distribution given in NASA report 1024<sup>24</sup> by adding foam buoyancy at the thighs and torso, which can be seen in the photograph, Fig. 7. A weight belt was used rather than placing the ballast weights in the dummy's instrument cavity, in order to achieve the proper center of gravity of the torso (which was also ballasted according to center of gravity data from NASA report 1024). One of the variations tested, referred to as the *light dummy*, was tested with the 6.3-lb weight belt removed. Dimensions and weights are shown for the 50th percentile in Fig. 8. Several important changes were made to the dummy, however, as a result of the problems documented in past tests. The neck was given a much lighter spring for a more compliant neck, and the joints were made looser, primarily by polishing and lubrication of bearing surfaces. Later in the test program a *Loose Joints* configuration was used by totally removing *Friction Disks* \* from each joint. Another dummy configuration tested was with clothes on, shown in Fig. 9. A sweatshirt, flannel shirt, pair of cotton slacks, shoes and socks brought the dry weight of the dummy to 160 lb. Tests were also conducted on the bare 50th percentile dummy with arms and legs tied up into the *Heat Escape Lessening Posture* † (HELP) position, with the body angles as shown in Fig.10.

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\* Friction disks are washer-like disks at each joint, that were originally designed to provide realistic joint friction.

† This is a survival posture recommended for minimum heat loss when the danger of hypothermia exists.

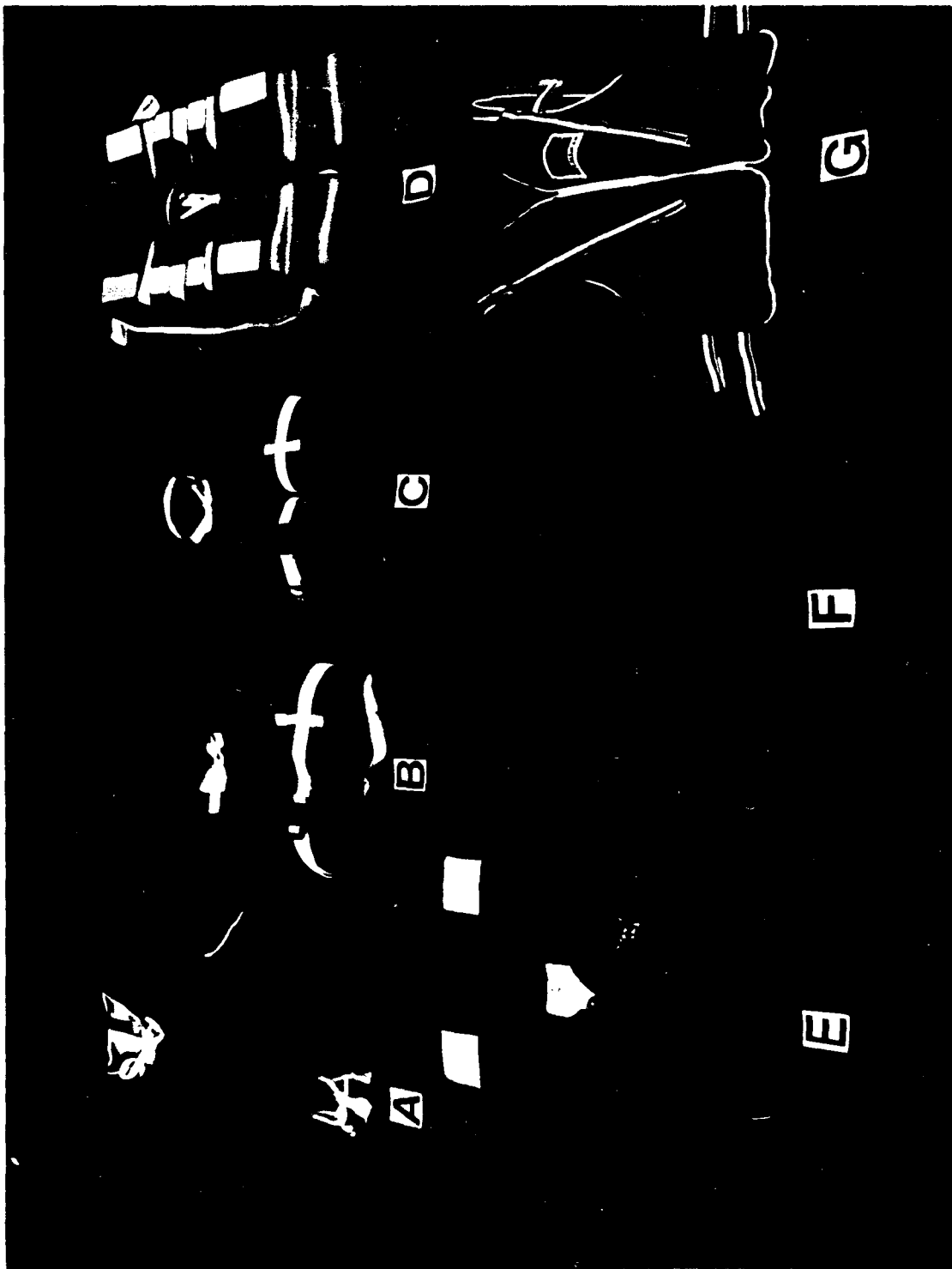


Fig. 6. Personal flotation devices (PFD's A-J) used in experiments.

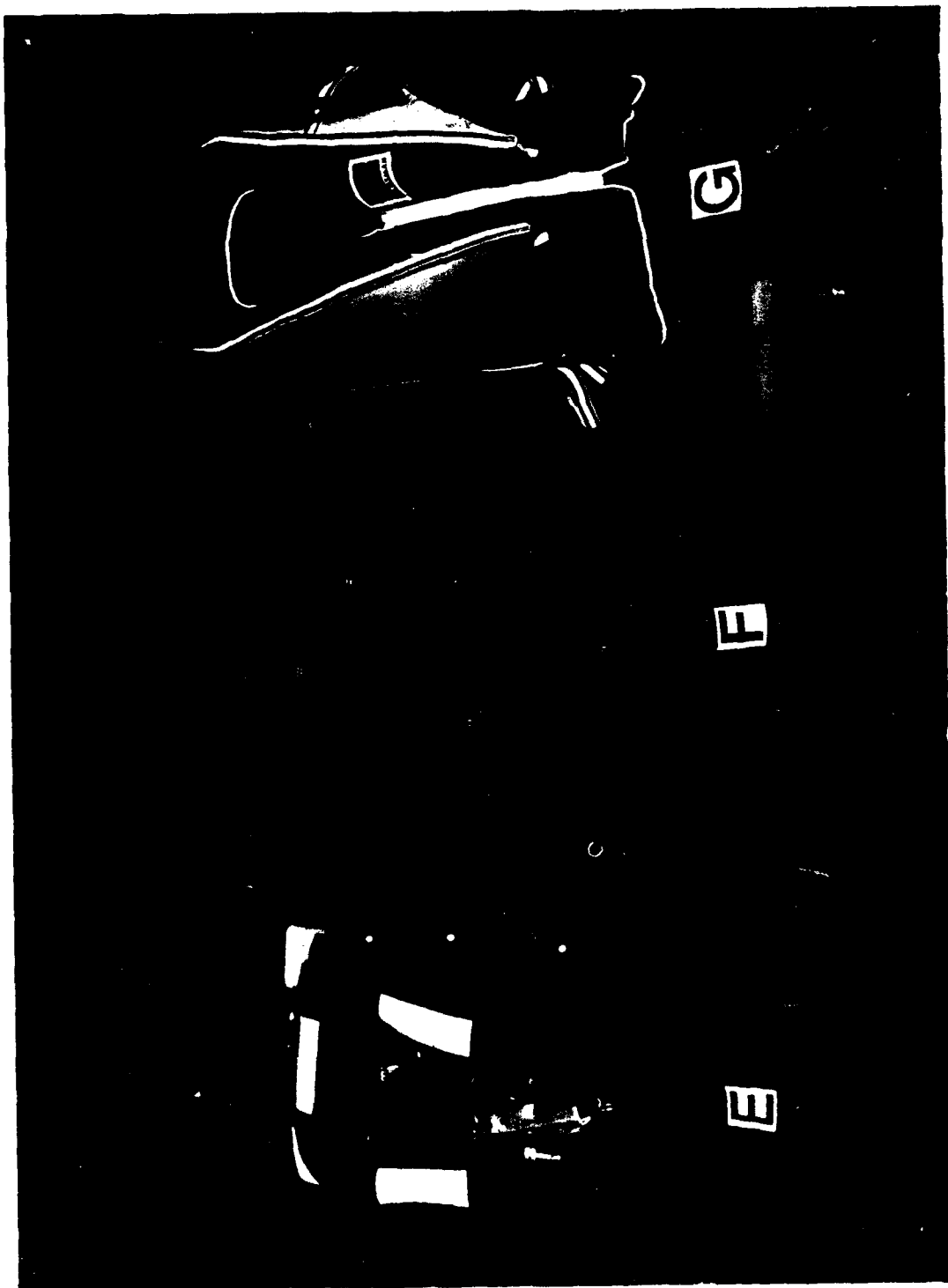


Fig. 6. (Continued)

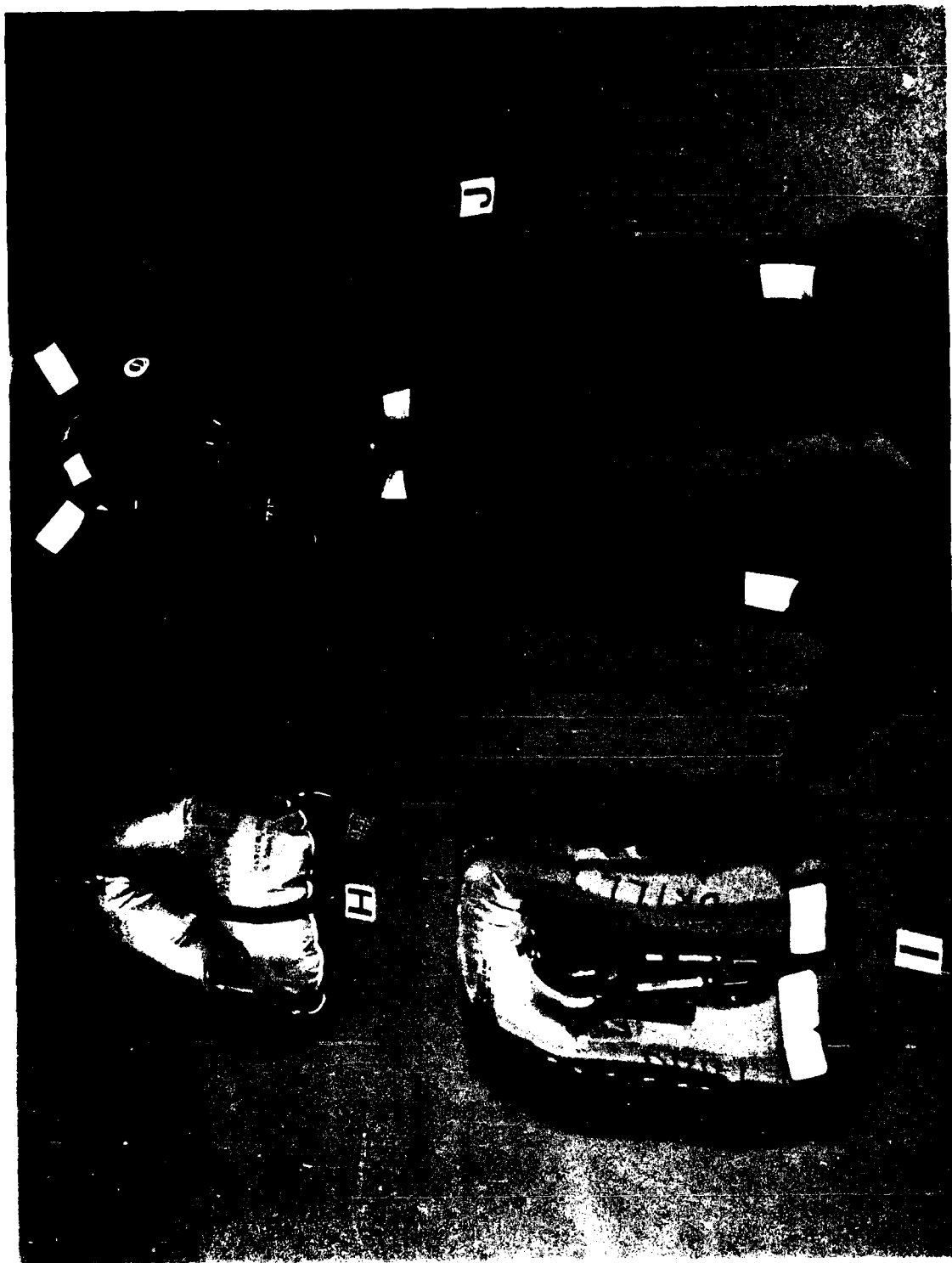


Fig. 6. (Continued)

Table 1. Anthropomorphic dummy characteristics.

DUMMY SEGMENTS	50th PERCENTILE DUMMY				LIGHT DUMMY			DUMMY WITH CLOTHES		
	WEIGHT in air lb	WEIGHT in water lb	SPECIFIC GRAVITY (test)	SPECIFIC GRAVITY (target)	WEIGHT in air lb	WEIGHT in water lb	SPECIFIC GRAVITY (test)	WEIGHT in air lb	WEIGHT in water lb	SPECIFIC GRAVITY (test)
HEAD (incl. connector & cable)	12.00	8.60*	1.24	1.11	12.00	8.60*	1.24	12.00	8.60*	1.24
TORSO (including Weight Belt)	72.06	-2.70	0.96	.85-1.01	65.76	-6.60	0.91	75.06	-2.70	0.97
ARMS										
Upper Arm-R	3.68	-0.05	0.99	1.07	3.68	-0.05	0.99	3.68	-0.05	0.99
Upper Arm-L	3.42	-0.35	0.91	1.07	3.42	-0.35	0.91	3.42	-0.35	0.91
ForeArm-R	2.84	0.50	1.21	1.12	2.84	0.50	1.21	2.84	0.50	1.21
ForeArm-L	2.86	0.65	1.29	1.12	2.86	0.65	1.29	2.86	0.65	1.29
Hand-R	1.06	0.25	1.31	1.10	1.06	0.25	1.31	1.06	0.25	1.31
Hand-L	1.04	0.20	1.24	1.10	1.04	0.20	1.24	1.04	0.20	1.24
LEGS										
Thigh-R	18.84	0.80	1.04	1.05	18.84	0.80	1.04	19.84	0.80	1.04
Thigh-L	18.26	-0.10	0.99	1.05	18.26	-0.10	0.99	19.26	-0.10	0.99
Shank-R	6.16	0.80	1.15	1.08	6.16	0.80	1.15	6.16	0.80	1.15
Shank-L	5.86	0.50	1.09	1.08	5.86	0.50	1.09	5.86	0.50	1.09
Foot-R	3.66	0.95	1.35	1.09	3.66	0.95	1.35	3.66	0.95	1.35
Foot-L	3.26	0.45	1.16	1.09	3.26	0.45	1.16	3.26	0.45	1.16
WEIGHT, totals	155 lb (in air)	10.5* lb (in water)			148.7 lb (in air)	6.6* lb (in water)		160 lb (in air)	10.5* lb (in water)	
Segment % Total†										
head+neck (8.4%)	7.7%				8.1%			7.5%		
torso (50%)	46.5%				44.2%			46.9%		
total arm (10.2%)	9.6%				10.0%			9.3%		
total leg (31.4%)	36.2%				37.7%			36.3%		
% Body Fat	17.6%	(calculated equivalent)			29.20%			19.1%		

\* Head submerged to chin & earlobe.  
† ( ) = Target weight distribution as a % of total.

\*Head submerged to chin & earlobe.

†( ) = Target weight distribution as a % of total.



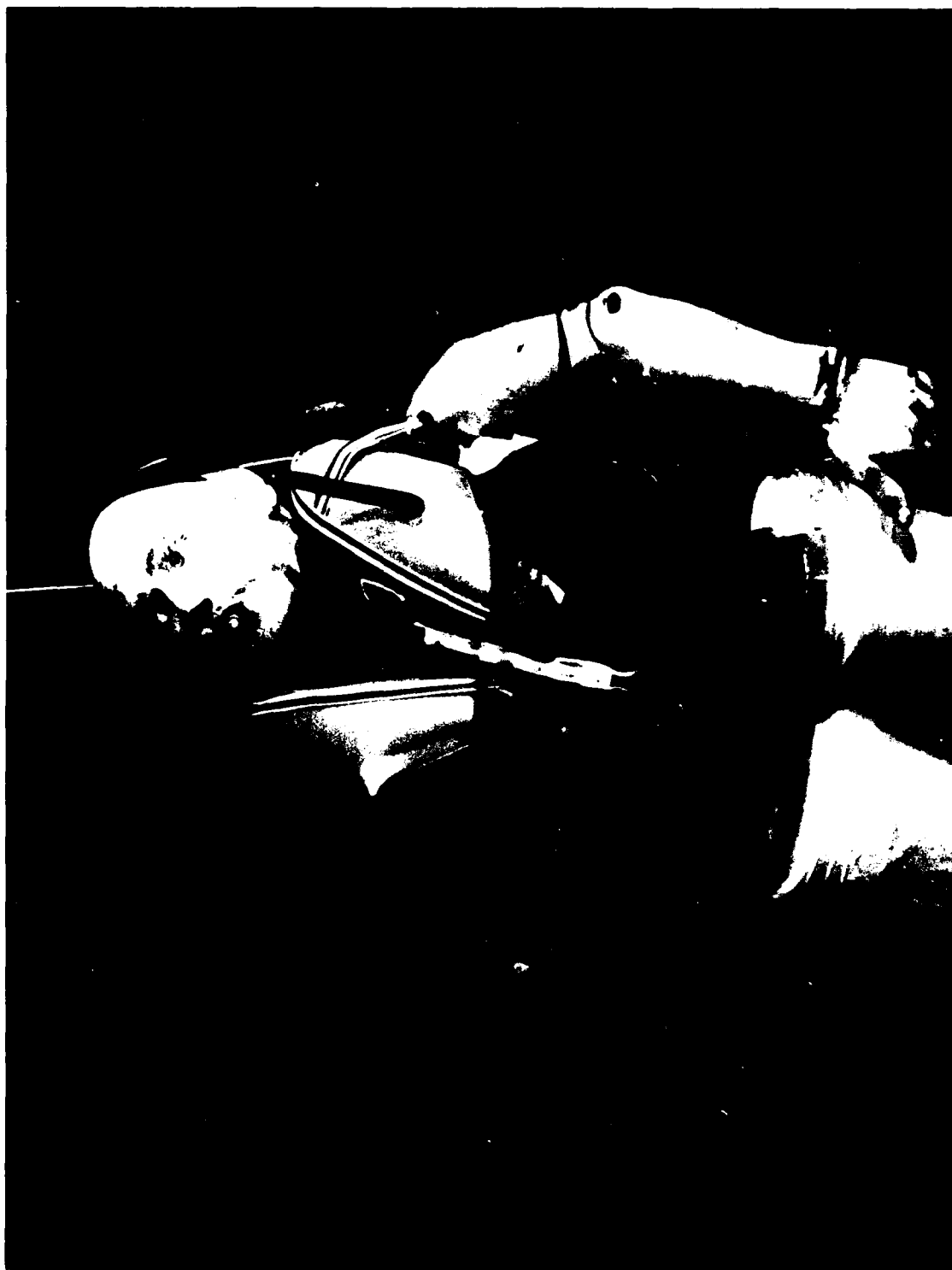


Fig. 7. Photograph of the dummy wearing PFD G (inflated).

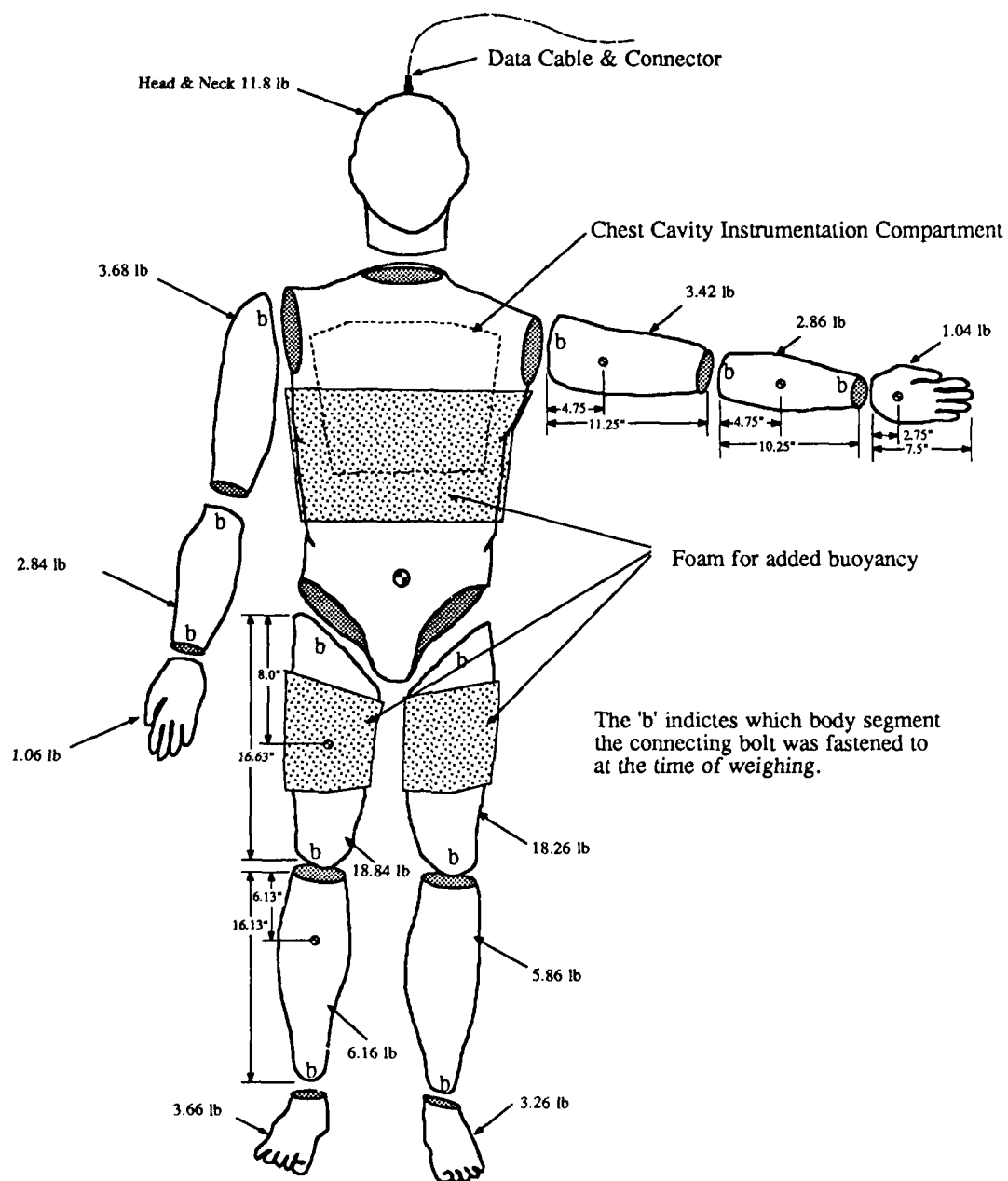


Fig. 8. Diagram of 50th percentile male anthropomorphic dummy, as tested.



Fig. 9. The anthropomorphic dummy with clothes.

### HELP Position on Dummy

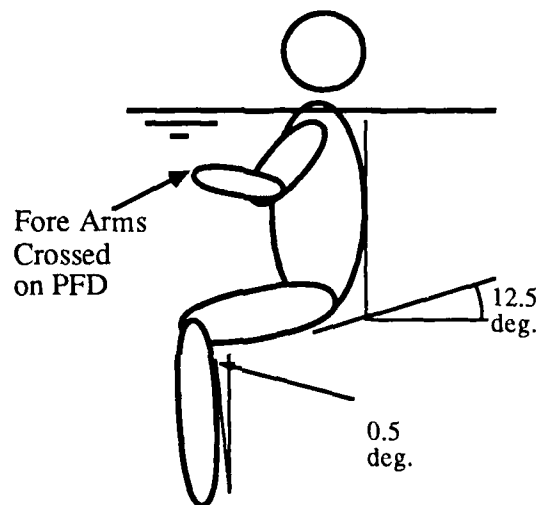


Fig. 10. Body reference angles for the 50th percentile dummy in the HELP position.

### DESCRIPTION OF HUMAN TEST SUBJECTS

Limited experiments were conducted using two human test subjects. Test Subject 1 was Samuel Wehr of the USCG, and Test Subject 2 was Christopher Hart of DTRC. Table 2 presents the relevant body characteristics of each, with a comparison to the 50th percentile dummy characteristics.

Table 2. Comparative body characteristics of human test subjects and 50th percentile anthropomorphic dummy.

	Test Subject 1	Test Subject 2	Dummy (50th%)
Height (inches)	71.5	64.5	68.5
Weight (lb)	160.	176.	155.
Chest Size (inches)	38.	40.	39.
Waist (inches)	32.	34.	32.
% Body Fat	16.2	25.	17.6 <sup>†</sup>
Buoyancy Requirement (lb)*	11.5	11.3	10.5

\* Subject's weight in water to earlobe and chin, wearing clothes

<sup>†</sup> An equivalent % body fat content based on dummy density

## TEST PROGRAM AND MEASUREMENT PROCEDURE

### *Test Program*

Experiments were conducted in three general phases. *First*, the weight and buoyancy characteristics of each PFD were determined from immersion tests. The *second* phase was to determine the flotation characteristics of each PFD on the 50th percentile dummy. The *third* phase was to repeat the flotation measurements using one PFD on several variations of the dummy's body characteristics, and to perform limited correlation with two human test subjects. An outline of the test plan and a description of each of the experiments are given in Fig. 11.

#### I. Measurement of PFD Weight and Buoyancy Characteristics

#### II. Measurement of Flotation Characteristics of PFD's on 50th Percentile Dummy

A. Static Flotation: Measure freeboard, static trim, faceplane angle, turning time

B. Oscillation - Measure natural period and damping

#### III. Measurement of the Effects of Body Variations for Single PFD (PFD G. Hybrid Helmsman/ERO)

##### A. Static Flotation and Oscillation Experiments on:

1. Dummy, Light Displacement (148.7 lb)
2. Dummy, Loose Joints (155 lb)
3. Dummy, With Clothes (160 lb)
4. Dummy in Help Position

##### B. Using Human Test Subjects

1. Test Subject 1 \*
2. Test Subject 2 \*

*\* Partial measurements only*

Fig. 11. Outline of test plan.

### Measurement of PFD Characteristics

The characteristics of weight and buoyancy were determined for each of the PFD's from immersion tests. Figure 12 shows a diagram of the test set-up. A large weight was suspended in water from a load cell on an overhead crane. The load cell was calibrated to read out the weight directly in pounds and was set to a reading of zero with the weight submerged. The PFD was then hung on the attachment point and its weight in air recorded. The PFD was then lowered until submerged and its weight in water was recorded. The weight in air was also recorded for the wet PFD after 2 minutes as a relative measure of water retention between PFD's.

The same apparatus and procedure were used to determine the weight and buoyancy of each of the segments of the anthropomorphic dummy for the calculation of body density and an equivalent percent body fat.

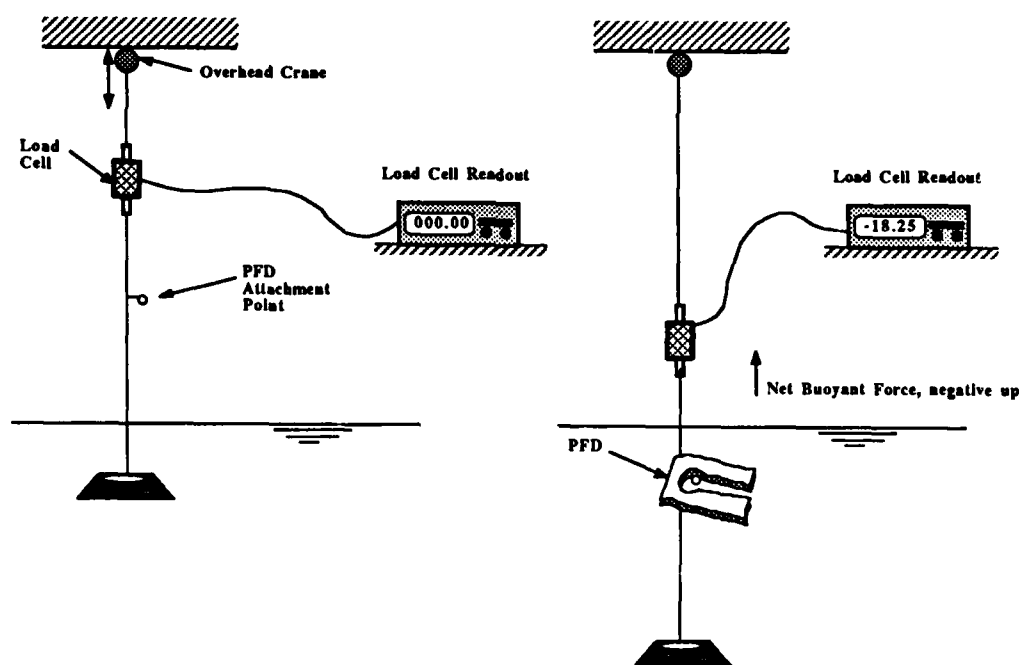


Fig. 12. Test apparatus for measuring PFD buoyancy.

### *Measurement of PFD Characteristics on Dummy and Test Subjects*

*Static Measurements.* The following measurements were recorded with PFD's on the 50th percentile dummy in calm water: freeboard, faceplane angle, torso (or body) angle, turning time, and waterplane area. *Freeboard* was measured as the distance from the water surface to the lowest point of the mouth using a floating scale provided by the Coast Guard. *Faceplane angle*, defined as the angle of the face, measured along side of the nose from the eyebrow to the upper lip, was determined using a hand held digital inclinometer. During the measurement of faceplane angles on human subjects, the head was allowed to tilt back with the neck relaxed, but was kept from tilting to one side or the other. The faceplane angle was translated into a *head angle* by subtracting the constant *slope* of the face from the faceplane angle. This slope was determined for the dummy and human subjects by measuring the faceplane angle of the subject lying on a horizontal flat surface. These slopes were determined to be approximately 10 degrees for the dummy, 10 degrees for Test Subject 1, and 5 degrees for Test Subject 2. The *torso angle* was defined as the angle between the dummy's torso and the water surface and determined from accelerometers mounted inside the dummy. Figure 13 shows how the angles were referenced relative to the water surface. Note that torso angle is referenced from vertical in these tests\*, and the faceplane angle from horizontal. *Turning time*, referred to as the time required for a PFD to rotate the dummy from a horizontal face down position until the mouth clears the water surface, was measured using a stopwatch. *Waterplane area*, the horizontal cross-sectional area of the dummy and PFD at the water surface, was determined by making measurements and noting where the waterline intersected the PFD. Later, these notes were used to reconstruct the shape of the waterplane in a computer graphics program, and an estimate of the area of each PFD was obtained. These approximations of the waterplane area profiles are shown in Appendix C.

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\* Other PFD researchers have referenced torso angle from the horizontal plane.

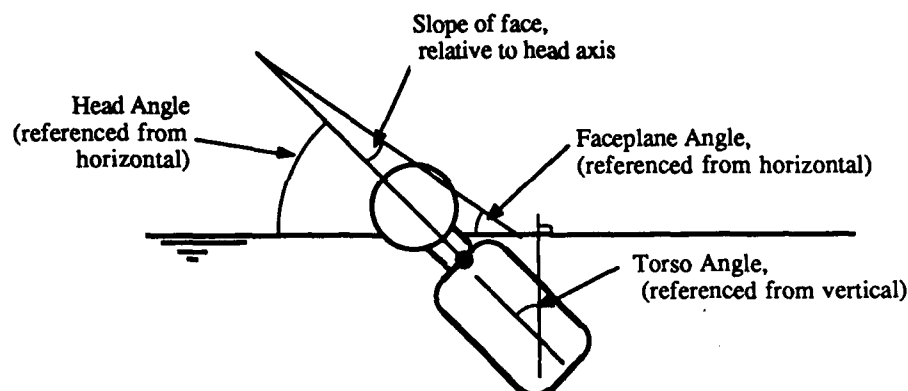


Fig. 13. Reference angle definitions.

*Oscillation Measurements.* For the oscillation experiments, an overhead beam was mounted from the end of a pier in the test facility. A lifting line was fastened to a harness under the arms of the dummy, and run vertically through a pulley on the beam and back to the pier, as shown in Fig.14. A string potentiometer mounted on the beam above the dummy was used to measure the vertical displacement of the dummy. For each test the dummy was raised partially out of the water and released. A digital computer and an analog strip chart recorder were used to record the oscillatory trace of the vertical motion. A sample time history trace is shown in Fig.15. Figure 16 shows the dummy wearing the Hybrid Helmsman/ERO PFD (G). The lifting line (white) and string from the string potentiometer (lighter line) are visible, as is the data transmission cable from the dummy's head.

An unexpected pitch oscillation was observed in the initial dummy tests, so a procedure was added to the test plan to isolate pitch natural frequencies at the various test conditions. The procedure involved raising the dummy's feet toward the water surface, *face up*, and releasing (not the same measurement as turning time). The dummy oscillated with a pendulum motion and a trace of the oscillation was obtained from accelerometer outputs.



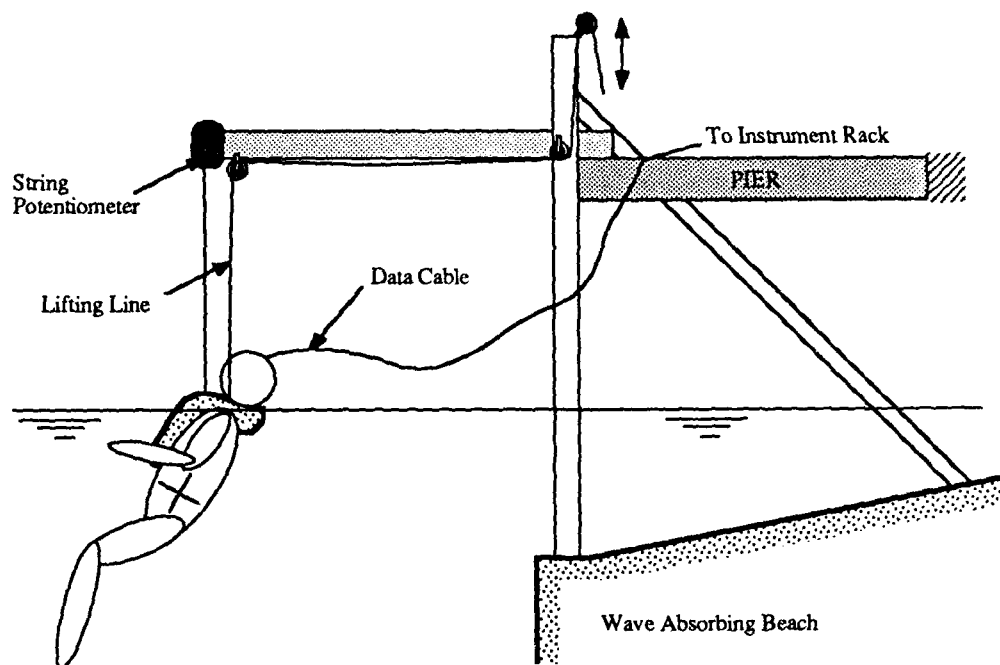


Fig. 14. Oscillation experimental set-up.

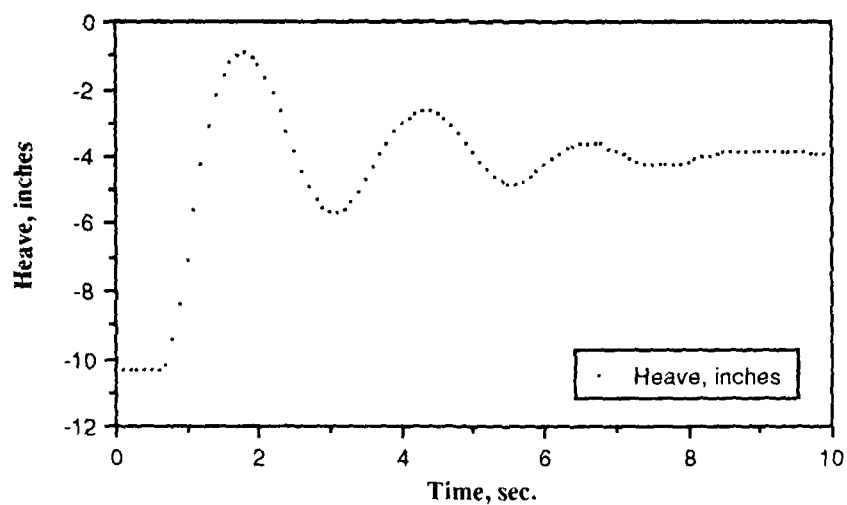


Fig. 15. Sample time history trace of heave oscillation (run 110).



Fig. 16. The 50th percentile dummy in the water wearing PFD (G), the Hybrid Helmsman/ERO (inflated).

*Measurements on Human Test Subjects.* Freeboard, faceplane angle and turning time were recorded for Test Subjects 1 and 2 wearing PFD G only. Test Subject 1 was instrumented with a vertical accelerometer as shown in Fig. 17, which provided a readout of torso angle. A harness similar to the dummy's was rigged to allow the lifting of the test subject for oscillation tests, and the string potentiometer was used to record the vertical motions. The test procedure for the human subjects was similar to that of the dummy, except that in the oscillation tests the effects of limb stiffness (relaxed versus rigid) were investigated. Also, oscillation tests were repeated with the subjects in the HELP position. Due to time constraints, Test Subject 2 was not instrumented with the accelerometer for torso angle reading.

It should be noted that while these test procedures are rather simple and straight forward, portions of the experiment took a great deal of time and effort. Particularly in preparing and ballasting the dummy, waterproofing the instrument cavity and setting up the test apparatus and data collection equipment. Waterplane area measurements and calculations were also difficult and time consuming, mainly because of the extremely irregular shape at the waterline. However, significant improvements in efficiency would be realized in large scale testing or in often repeated experiments, once the procedures have been established. This would be particularly true if a new set of standard flotation dummies were developed that could be tested "off the shelf" (i.e., without extensive refurbishing, weighing and ballasting).



Fig. 17. Test subject 1, Samuel Wehr, instrumented with a vertical accelerometer on PFD G.

## DESCRIPTION OF INSTRUMENTATION

Details of the specific instrumentation used in the experiments are given below. Two devices were used for the weighing of PFD's and dummy parts, depending on the accuracy required. A National Controls, Inc. (NCI) model 5785 electronic platform scale of 200 lb capacity, with a precision of  $\pm .02$  lb, was used for all dry weight measurements. An NCI 5400 electronic load cell with 500 lb capacity, with a precision of  $\pm .05$  lb, was used for all buoyancy (weight in water) measurements. Freeboard measurements were taken using a floating vertical scale, provided by the Coast Guard, which was calibrated in one-half inch increments and had a resolution of approximately  $\pm .25$  in. Faceplane angles were recorded using a Sperry hand held electronic inclinometer, capable of reading any angle to within  $\pm 0.1$  degrees.\* Torso angle measurements of the dummy were calculated from the output of two accelerometers, one vertical and one horizontal, mounted inside the dummy's instrument cavity in the chest area. Details of the accelerometer calibrations are given in Appendix D. Heave displacement was measured with a string potentiometer. A string potentiometer is a device with a spring loaded coil of fine wire mounted to a potentiometer in an enclosure, such that as the wire is drawn in and out, a voltage proportional to distance is output. The accelerometer and heave (vertical) displacement measurements were recorded on a Gulton 4-channel strip chart recorder for immediate observation. An Interdata model 70 computer with an Analogic A to D converter was used to digitize and record signals to digital magnetic tape, at a rate of 10 samples/second/channel.

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\* The accuracy of the measurement was approximately  $\pm 3$  degrees based on multiple readings, due to inaccuracies in placing the transducer on the subject, in the water.

## PRESENTATION OF DATA

### PFD Characteristics

The weight and buoyancy characteristics of each PFD, from immersion tests, are presented in Table 3\* along with calculations of the displacement, volume and specific weight of each. Figure 18 shows the range of weights and buoyancies (note: total bar graph height equals displacement). Details of the buoyancy calculation procedure are given in Appendix E. *Specific weight* is provided as a measure of the PFD's density in lb/cu.ft. Of all the PFD's tested, the inflated Hybrid Helmsman/ERO (PFD G) has the lowest specific weight or density of any of the PFD's and it was also the lightest. Since it is one of the more comfortable PFD's to wear (in the authors' opinion), PFD density and weight may be good indicators of wearability.

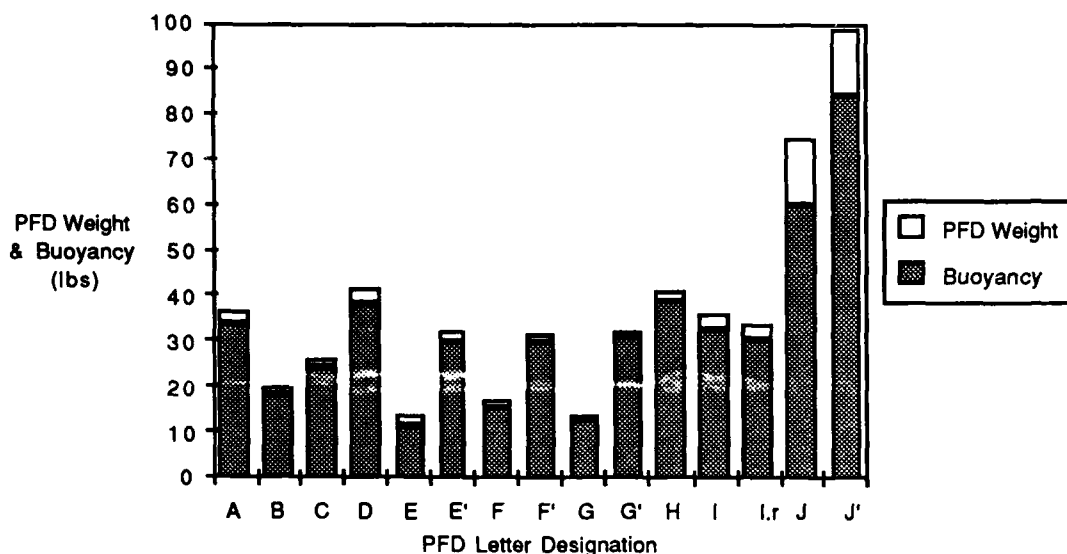


Fig. 18. Weight and buoyancy characteristics of PFD's tested.

It should also be noted that the buoyancy rating listed on a PFD is often the minimum buoyancy required in its category and not the actual measured buoyancy, which can be notably higher. For example

\* The primes (single quote marks) on the PFD letter designations, E', F', G', and J' denote the inflated condition, and I.r denotes the reserve chamber was inflated.

the Hybrid Helmsman PFD has an inherent buoyancy of 12.7 lb, nearly twice the required 7.5 lb, and inflated it has a total buoyancy of 31 lb, where the minimum required is 22 lb. Therefore in evaluating PFD's, care should be taken to use actual, as opposed to the rated buoyancy for comparative purposes.

#### *PFD Characteristics on Dummy and Test Subjects.*

The results of calm water flotation and oscillation experiments are presented in Table 4a-4c for the three sets of tests, respectively: (1) all PFD's on the 50th percentile dummy, (2) PFD (G) on several dummy variants, (3) PFD (G) on human test subjects. Included are measurements of freeboard, calm water flotation angles, turn time, waterplane areas, natural periods, and log decrements (calculated from free decay data). Some of the turning times are noted as having been calculated from the strip chart trace as the time for the torso angle to rotate from horizontal to vertical (through 90 degrees). This was done after the experiment for cases where stopwatch readings were not obtained during the test. These calculations are probably a conservative estimate of turning time since in actuality the mouth generally cleared the water surface prior to the torso reaching a completely vertical position.

Figure 19a-c presents the range of natural periods for the three test sets, respectively. The corresponding damping factors (calculated from Eq. 9 using decrement data) are presented in Figs. 20 a-c. Figure 20c includes results of the specific actions taken by the human test subjects (body relaxed, rigid, etc.) and are referenced to Table 4c data via a *Reference Run Number*. Figures 21a and 21b are given as a sample of the analysis of data used to calculate the log decrements and subsequently the damping factor. The slope of a straight line least squares fit through a semi-log plot of heave amplitude decay, corresponds to the log decrement calculated using Eq. 8. The regression correlation coefficients for data presented were all between 0.98 and 1.0 with most being better than 0.99.

Tables 5a and 5b present the results of calculations using the mass of dummy plus PFD's, waterplane areas, natural heave periods and log decrements, to determine undamped natural frequencies, added masses, damping factors and hydrodynamic coefficients for tests using the dummy.

Table 3. PFD buoyancy characteristics.

PFD Test Reference Designation	USCG Supplied PFDs	Weight in Air		Weight in Air twet, lbs.	Buoyancy B, lbs. (neg.=up) (Weight in Water)	Displacement D, lbs (submerged)	PFD Volume V, cu.ft.	Specific Weight lbs/cu.ft SpWt=W/V
		W, dry, lbs.	W, wet, lbs.					
A	Type I, Kapok, Gladding, (Dec.77)*	2.76	3.66		-34.15	36.9	0.59	4.66
B	Type II, Kapok, Crawford (Ref #II)*	1.54	1.8		-18.3	19.8	0.32	4.83
C	Reference Vest for Hybrids ( Sample #2)	1.68	1.93		-24.5	26.2	0.42	4.00
D	Type V, Jetfoil, R. Perry	2.74	3.03		-38.7	41.4	0.67	4.12
E	Hybrid, Stearns Work Vest Sample, IWH-302	2.4	3.35		-11.4	13.8	0.22	10.83
E'	Hybrid, Stearns, above PFD, Inflated	2.4	3.35		-29.95	32.4	0.52	4.62
F	Hybrid Sample 218 (Wyle)*, Uninflated	1.7	2.45		-15.3	17.0	0.27	6.23
F'	Hybrid Sample 218 (Wyle)*, Inflated	1.7	2.45		-30	31.7	0.51	3.34
G	Hybrid Helmsman/ERO, Uninflated	1.16	1.66		-12.65	13.8	0.22	5.23
G'	Hybrid Helmsman/ERO, Inflated	1.16	1.66		-31.00	32.2	0.52	2.25
H	Sonoform Commercial Inflatable, BHP-010-3	2.08	2.35		-39	41.1	0.66	3.15
I	Sonoform Military Inflatable, main bladder (#LPU-26/P)	3.13	3.9		-32.9	36.0	0.58	5.41
I,r	Sonoform Military Inflatable, reserve bladder (#LPU-26/P)	3.13	3.9		-30.7	33.8	0.54	5.76
J	Mustang Exposure Suit, Uninflated	14.6	-		-60.00	74.6	1.20	12.19
J'	Mustang Exposure Suit, Inflated	14.6	-		-84.00	98.6	1.58	9.22

\* First Test Priority PFDs

† After approx. 2 minutes out of water

Table 4. Results of flotation and oscillation experiments.

Table 4a. Results of flotation and oscillation experiments for PFD's on 50th percentile dummy.

PFD Test Reference Designation	USCG Supplied PFDs	Freeboard inches	Faceplane Angle,deg. from horiz.	Head Angle,deg. from horiz.	Torso Angle degrees from vert.	Turning Time,sec.	Waterplane Area, sq.ft.	Natural Heave Period, sec.	Log Decrement of Heave	Natural Pitch Period, sec.	Log Decrement of Pitch
A	Type I, Kapok, Gladding, (Dec. 77)	5.5	11.5	1.5	49.3	1.1 (1.7*)	2.32	1.6	0.67	4.6	0.38
B	Type II, Kapok, Crawford (Ref #II)	4.0	32.0	22.0	37.8	2.5	1.26	1.8	0.47	6.0	0.39
C	Reference Vest for Hybrids ( Sample #2)	3.8	30.5	20.5	40.6	1.9	1.22	1.7	0.62	5.1	0.39
D	Type V, Jetfoil, R. Perry	5.5	67.0	57.0	27.8	1.6*	1.42	1.4	0.36	3.6	0.36
E	Hybrid, Stearns Work Vest Sample,IWH-302	-1.0	71.0	61.0	16.5	no turn	?	3.2	0.54	6.7	0.54
E'	Hybrid, Stearns, above PFD, Inflated	3.0	64.0	54.0	28.5	1.9*	?	1.7	0.69	4.7	0.43
F	Hybrid Sample 218 (Wyle), Uninflated	2.0	37.0	27.0	31.5	5.6	0.54	3.1	0.29	8.0	0.57
F'	Hybrid Sample 218 (Wyle), Inflated	5.0	8.5	-1.5	52.3	1.7	1.52	1.6	0.50	4.7	0.40
G	Hybrid Helmsman/ERO, Uninflated	3.5	27.5	17.5	42.0	7.0	1.06	2.5	0.64	8.2	0.45
G'	Hybrid Helmsman/ERO, Inflated	4.5	52.5	42.5	37.3	3.0	1.69	1.8	0.64	5.9	0.38
H	Sonoform Commercial Inflatable, BHP-010-3	2.3	90.5	80.5	-0.3	N/A	1.83	1.6	0.41	4.5	0.35
I	Sonoform Military Inflatable, (#LPU-26/P)	4.5	45.0	35.0	31.6	1.7	2.05	1.7	0.71	3.7	0.67
J	Mustang Exposure Suit, Uninflated	1.5	-30.0	-40.0	84.5	no turn	5.27	no cycles	no cycles	no cycles	no cycles
J'	Mustang Exposure Suit, Inflated	3.3	22.0	12.0	79.2	no turn	7.38	no cycles	no cycles	no cycles	no cycles

\* Calculated from angle data, as the time required to rotate from horizontal to vertical position.

\* Calculated from angular data, as the time required to rotate from horizontal to vertical position.



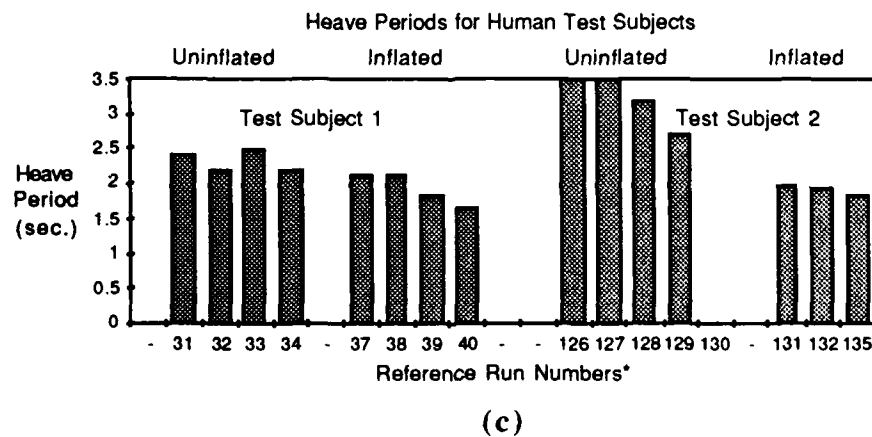
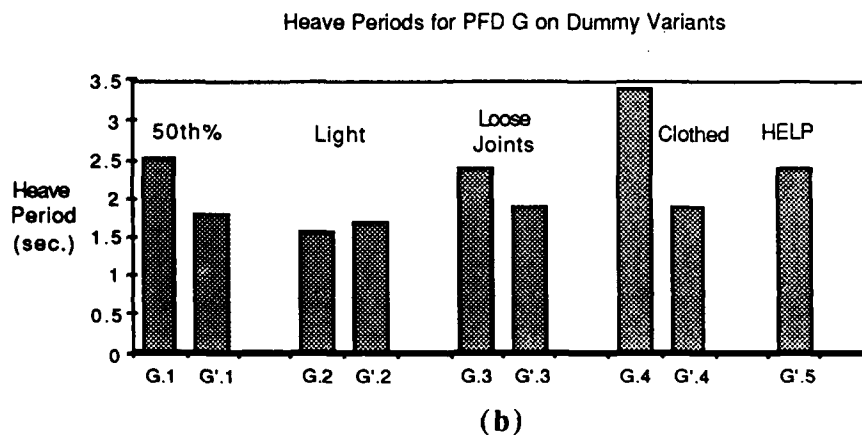
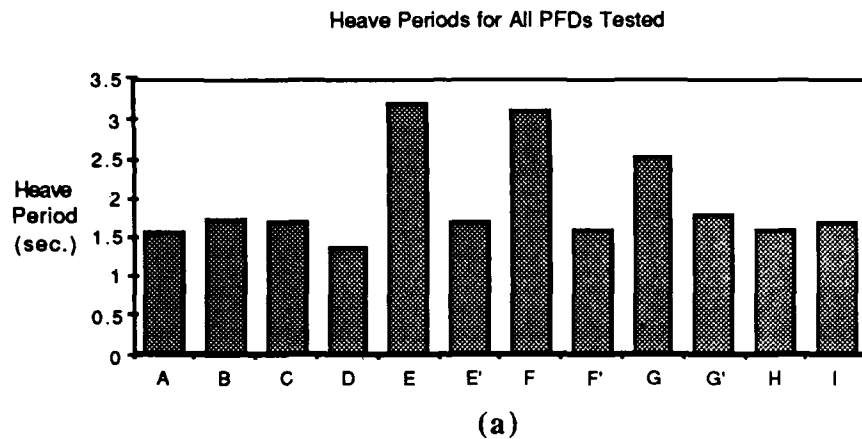
**Table 4b. Results of flotation and oscillation experiments for PFD (G) on dummy variants.**

PFD Test Reference Designation	Test Subject / Configuration	Freeboard inches	Faceplane Angle, deg. from horiz.	Head Angle, deg. from horiz.	Torso Angle degrees from vert.	Turning Time, sec.	Waterplane Area, sq.ft.	Natural Heave Period, sec.	Log Decrement of Heave	Natural Pitch Period, sec.	Log Decrement of Pitch
G'.1 G'.1	50th Percentile Dummy - PFD Uninflated - PFD Inflated	3.5 4.5	27.5 52.5	17.5 42.5	42.0 37.3	7.0 3.0	1.06 1.69	2.5 1.8	0.64 0.64	8.2 5.9	0.45 0.38
G'.2 G'.2	Dummy; Light Displ. - PFD Uninflated - PFD Inflated	3.5 4.5	-0.5 42.0	-10.5 32.0	62.7 57.3	5.5 1.5	- -	1.6 1.7	0.62 0.66	5.6 7.4	0.50 0.56
G'.3 G'.3	Dummy; Loose Joints - PFD Uninflated - PFD Inflated	3.5 4.5	14.5 46.0	4.5 36.1	47.5 41.7	no turn 3.8	- -	2.4 1.9	0.95 0.70	7.2 5.8	0.70 0.38
G'.4 G'.4	Dummy; with Clothes - PFD Uninflated - PFD Inflated	2.5 4.3	33.0 55.0	23.0 45.0	31.8 34.9	5.0 4.0	- -	3.4 1.9	1.05 0.63	11.0 7.2	1.25 1.20
G'.5	Dummy; HELP Position - PFD Inflated	2.5	103.5	93.5	-12.4	N/A	0.83	2.4	0.51	8.4	0.55

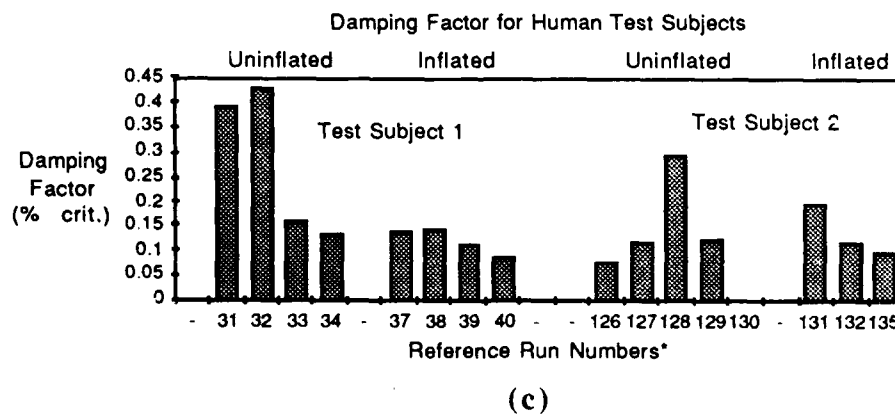
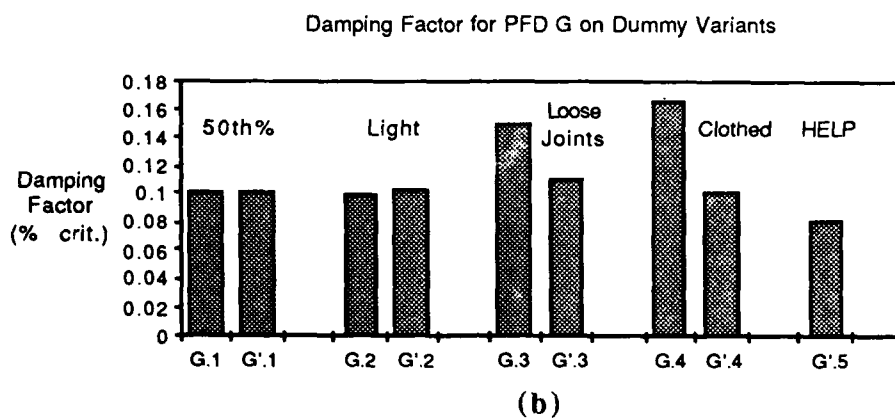
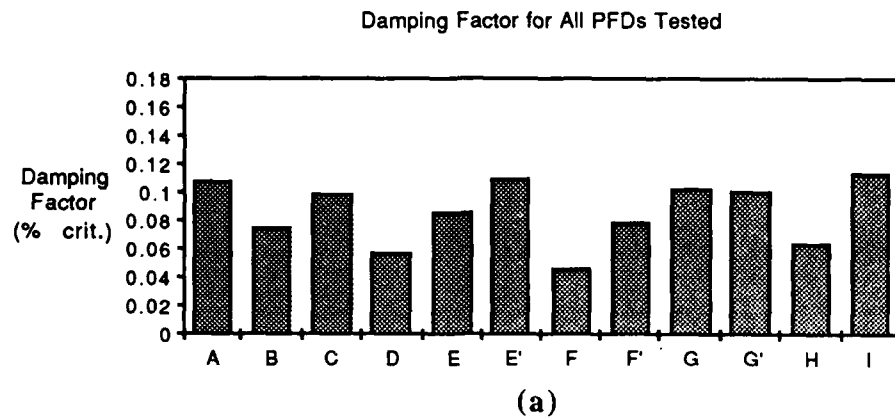
\* Calculated from angular data, as the time required to rotate from horizontal to vertical position.

**Table 4c. Results of flotation and oscillation experiments for PFD (G) on human test subjects.**

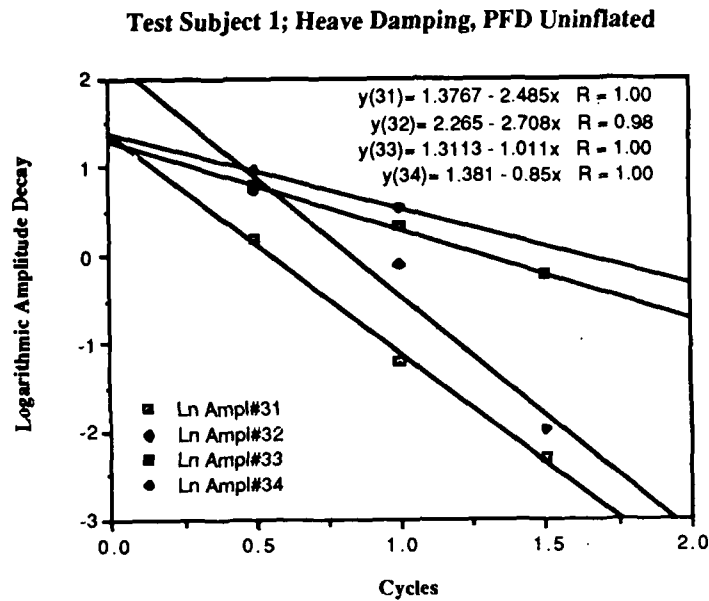
PFD Test Reference Designation	Test Subject / Configuration	Freeboard inches	Faceplane Angle, deg. from horiz.	Head Angle, deg. from horiz.	Torso Angle degrees from vert.	Turning Time, sec.	Waterplane Area, sq.ft.	Natural Heave Period, sec.	Log Decrement of Heave	Notes/Comments
G'.SW	Sam Wehr Body Relaxed, held breath Body Relaxed Body Rigid HELP Position	4.0	1.5	- - - -	58.01(rigid) 58.6(relaxed) - -	no turn - - unstable	N/A - - -	- 2.4 2.2 2.5 2.2	- 2.49 2.71 1.01 0.85	Reference Run #'s 31 32 33 34
G'.SW	Sam Wehr Body Relaxed Body Relaxed, higher amplitude Body Rigid HELP Position	5.0	31.8	- - - -	42.86(rigid) 45.74(relaxed) - -	no turn - - -	1.28 - - -	- 2.2 2.2 1.8 1.7	- 0.90 0.92 0.73 0.58	Reference Run #'s 37 38 39 40
G'.CH	Chris Hart Body Rigid, head upright Body Relaxed, head upright Body Relaxed, head back Body Rigid, head back HELP Position, unstable	N/A	N/A	- - - -	N/A - - -	unstable (face down)	N/A - - -	- 3.5 3.5 2.7 3.07	- 0.48 0.76 1.87 0.79 1 cycle	Reference Run #'s 126 127 128 129 130
G'.CH	Chris Hart Body Relaxed Body Rigid HELP Position	2.5	69.0	- - - unstable	- - - -	4.7 - - -	- - - -	- 2.0 2.0 1.9	- 1.24 0.77 0.63	Reference Run #'s 131 132 135



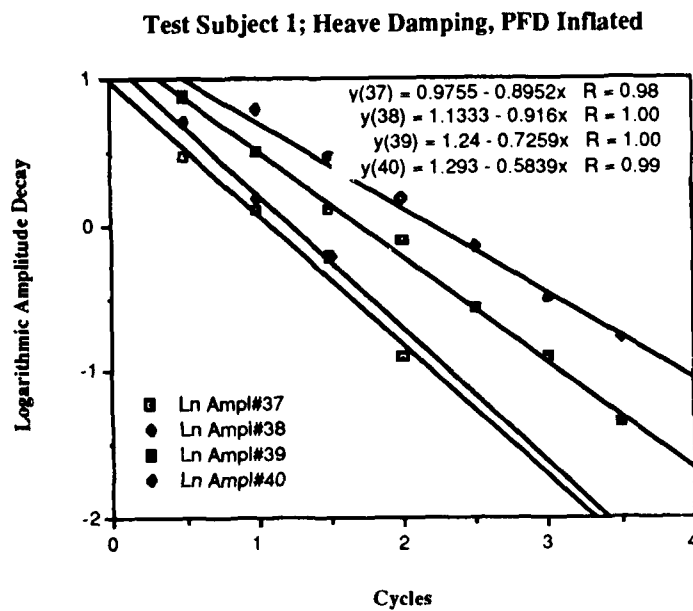
**Fig. 19.** Comparison of natural heave periods for (a) all PFD's on the 50th percentile dummy, (b) PFD (G) on the dummy variants, and (c) PFD (G) on the human test subjects.



**Fig. 20.** Comparison of damping factors for (a) all PFD's on the 50th percentile dummy, (b) PFD (G) on the dummy variants, and (c) PFD (G) on the human test subjects.



**Fig. 21a** Sample log decrement plots, Test Subject 1 in PFD G, Uninflated .



**Fig. 21b.** Sample log decrement plots, Test Subject 1 in PFD G, inflated.

**Fig. 21.** Sample logarithmic decay plots, used in the calculation of damping factors.

Table 5. Calculation of hydrodynamic coefficients from oscillation test data.

Table 5a. Calculation of hydrodynamic coefficients for PFD (G) on 50th percentile dummy.

PFD Test Reference Designation	Weight PFD+Dummy Lbs	Natural Period measured, sec.	Damped Natural Frequency, r/s Wd. measured	Logarithmic Decrement	Waterplane Area, wpa sqft	Critical Damping	Added Mass, as % of Mass	Mass Slugs	Natural Frequency Wn, calc., r/s	Damping Ratio	Added Mass, Slugs	Damping Coefficient, b	Restoration Coefficient, c
A	157.160	1.55	4.05	0.6734	2.319	70.865	77.235	4.903	4.077	0.107	3.787	7.595	144.463
B	156.540	1.750	3.59	0.470	1.264	43.739	24.841	4.865	3.600	0.075	1.209	3.274	78.741
C	156.680	1.700	3.70	0.617	1.215	40.759	12.681	4.870	3.714	0.098	4.003	4.003	75.689
D	157.740	1.380	4.55	0.360	1.417	38.711	-13.432	4.903	4.561	0.057	-0.659	2.220	88.272
E	157.400	3.200	1.96	0.540	-	-	-	4.892	1.971	0.086	-	-	-
E'	157.400	1.700	3.70	0.691	-	-	-	4.892	3.719	0.110	-	-	-
F	156.700	3.100	2.03	0.291	0.536	32.913	66.528	4.870	2.029	0.046	3.240	1.524	33.390
F'	156.700	1.600	3.93	0.501	1.521	48.103	25.352	4.870	3.940	0.080	1.235	3.836	94.751
G	156.160	2.530	2.48	0.644	1.056	52.698	117.445	4.854	2.497	0.102	5.700	5.401	65.784
G'	156.160	1.800	3.49	0.639	1.694	60.150	76.595	4.854	3.509	0.102	3.718	6.114	105.528
H	157.080	1.600	3.93	0.409	1.830	57.937	50.773	4.882	3.935	0.065	2.479	3.774	114.000
I	158.130	1.700	3.70	0.711	2.050	68.661	87.775	4.915	3.720	0.113	4.314	7.772	127.705
J	169.600	no cycles	-	no cycles	5.271	-	-	5.271	-	-	-	-	328.359
J'	169.600	no cycles	-	no cycles	7.382	-	-	5.271	-	-	-	-	459.864

Table 5b. Calculation of hydrodynamic coefficients for PFD (G) on dummy variants.

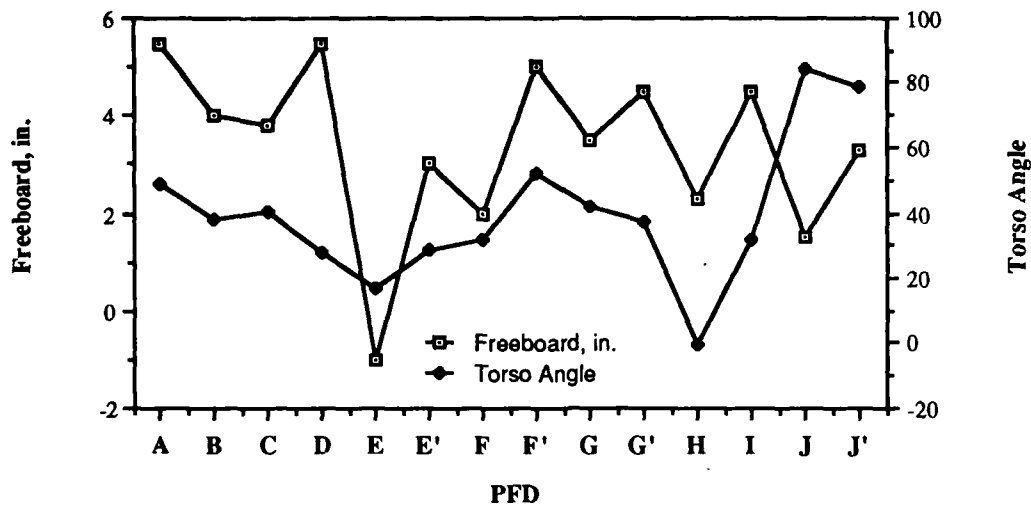
PFD Test Reference Designation	Weight PFD+Dummy Lbs	Natural Period measured, sec.	Damped Natural Frequency, r/s Wd. measured	Logarithmic Decrement	Waterplane Area, wpa sqft	Critical Damping	Added Mass, as % of Mass	Mass Slugs	Natural Frequency Wn, calc., r/s	Damping Ratio	Added Mass, Slugs	Damping Coefficient, b	Restoration Coefficient, c
G.1	156.160	2.53	2.48	0.644	1.056	52.698	117.445	4.854	2.497	0.102	5.700	5.401	65.784
G'.1	156.160	1.8	3.49	0.6387	1.694	60.150	76.595	4.854	3.509	0.102	3.718	6.114	105.528
G.2	149.900	1.55	4.05	0.6248	-	-	-	4.659	4.074	0.099	-	-	-
G'.2	149.900	1.7	3.70	0.6555	-	-	-	4.659	3.716	0.104	-	-	-
G.3	156.160	2.4	2.62	0.9492	-	-	-	4.854	2.648	0.151	-	-	-
G'.3	156.160	1.9	3.31	0.7021	-	-	-	4.854	3.328	0.112	-	-	-
G.4	161.160	3.4	1.85	1.0484	-	-	-	5.009	1.874	0.167	-	-	-
G'.4	161.160	1.9	3.31	0.6327	-	-	-	5.009	3.324	0.101	-	-	-
G'.5	156.160	2.4	2.62	0.5122	0.827	39.226	53.838	4.854	2.627	0.082	2.613	3.198	51.518

## DISCUSSION OF RESULTS

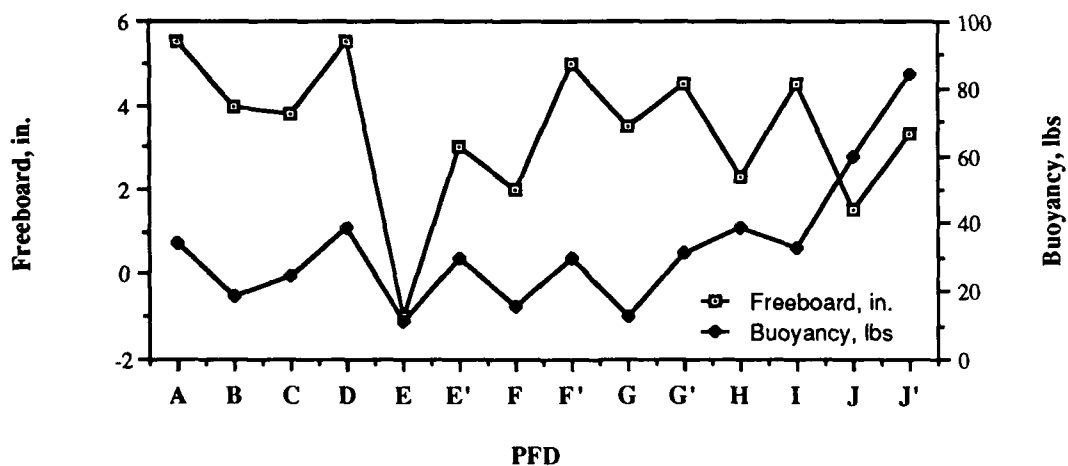
### *PFD's on 50th Percentile Dummy*

The results of static flotation tests made sense based on the differences in geometry of the various PFD designs, however, no simple and consistent relationships emerged between the various flotation measurements (see cross plots Figs. 22 a-c). Freeboard, for example could be increased by one of three ways: by the head (and or torso) being tilted farther back (raising the mouth away from water surface), by increased PFD buoyancy, and by having the buoyancy lower on the torso (thus submerging more of the PFD and less of the person). The Perry PFD (D) and the Sonoform PFD (H) both have about 39 lb of buoyancy, and both tend to orient the dummy in an upright position. The Perry PFD (D) has much of its volume underwater, distributed on chest and back, thus giving greater freeboard. It also provides somewhat more of an inclined torso angle, and the head is tilted back 20 degrees more. Sonoform (H) is worn much higher on the shoulders and consequently most of its volume is out of the water (not providing buoyancy) and the freeboard is therefore less than half that of the Perry (2.3 in. vs 5.5 in.). However, this high out of water part of the PFD could be thought of as *reserve buoyancy* and may prove to be valuable in waves. This tradeoff between reserve buoyancy and freeboard should be investigated in future studies (experimental or theoretical).

The turning times appeared to be a good measure of relative righting capability, with the fastest times for PFD's with high buoyancy and with buoyancy located further out on the front of the chest. It would have been desirable to measure the turning moment, but no practical test rig was achieved to account for PFD emergence/submergence at the free surface (and the subsequent effect on centers of buoyancy and turning moment), as a function of torso angle. The uninflated Stearns PFD (E) and both the uninflated and inflated survival suit (PFD J) were unable to effect a turn in the turn tests. The survival suit was noticeably stable in both the face up and face down positions.



**Fig. 22a.** Cross plot of freeboard and torso angle for all PFD's tested on the 50th percentile dummy.



**Fig. 22b.** Cross plot of freeboard and PFD buoyancy for all PFD's tested on the 50th percentile dummy.

**Fig. 22.** Cross plots of various calm water flotation characteristics for all PFD's tested on the 50th percentile dummy

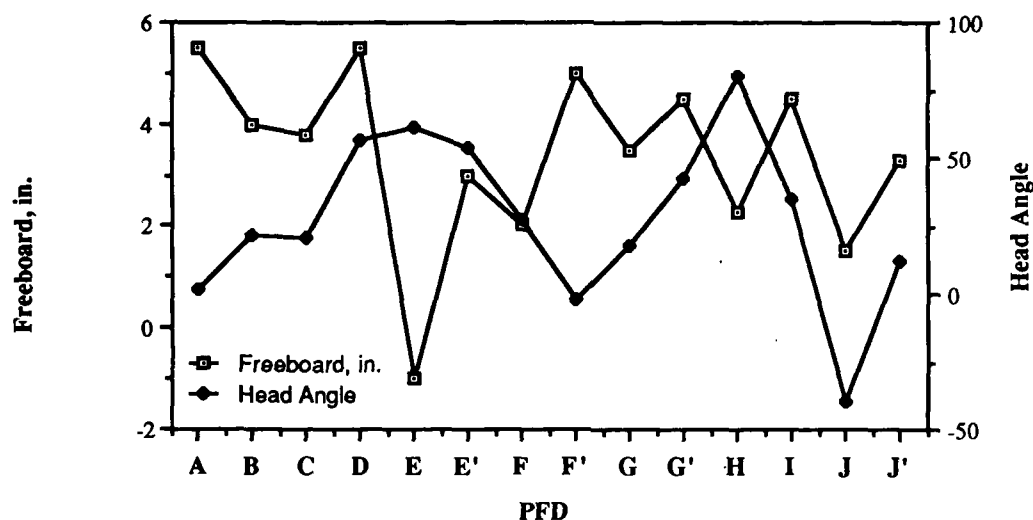


Fig. 22c. Cross plot of freeboard and head angle for all PFD's tested on the 50th percentile dummy.

Fig. 22. (Continued)

The range of heave natural periods for all tests was from 1.4 to 3.5 seconds as shown graphically in Fig. 19. The natural periods and damping characteristics determined in heave and pitch modes from free decay oscillation data, in most cases represented the average of at least two drop tests. The pitch natural periods, though listed are not considered to be of primary importance,\* and are presented mainly for future study (and analytical comparison). The highest periods were typically for uninflated hybrids ( $\approx 2.5$ -3.2 sec.) with very little waterplane area. The PFD's providing lower natural frequencies (higher periods) would probably have worse performance in waves, since there is likely to be more energy present in a typical seaway in this frequency range. The heave period and damping could not be obtained for the survival suit PFD (J) because of its high damping characteristics and large waterplane area. In general, the performance of the hybrid PFD's showed good agreement with the Reference Vest for hybrids, PFD (C).

\*Pitch was not significant enough to be measurable on human test subjects, but was 'sensed' by Test Subject 1, while maintaining a rigid posture in the water



The hybrid PFD's also provided good head support and turning moment when inflated. In most cases the head angle became more vertical while the torso angle became more horizontal after inflation (thus indicating increased stability and freeboard).

It should be mentioned that the Sonoform military PFD (I) (see Fig. 23) was added late in the test program because the USCG needed some basic comparative flotation data to evaluate that design, and had not yet been able to put it through all of the standard flotation tests normally used in the evaluation process. The data for this PFD on the dummy were then compared (quantitatively) to the others in the group for which better historical data on performance was known. This provided at least some initial information on a new device without the time and expense of setting up a full series of tests. This is a good example of the value of utilizing a dummy for comparing and evaluating the performance of PFD's.

#### *PFD G on Dummy Variants*

Results of tests on variations of the dummy: light (displacement), loose joints, clothed, and in the HELP position provide some measure of comparison of these effects on performance. Most noticeable is the result that the freeboards and natural heave frequencies remain relatively consistent among the variants (Tables 4b, 5b, and Figs. 19b, 20b). The natural heave frequency varies with mass, and waterplane area as would be expected from rigid body theory. According to Eq. 3, an increase in mass should reduce the natural frequency (or lengthen the period), and an increase in waterplane area should increase the natural frequency (or reduce the period). The dummy in the HELP position was unstable, and had a tendency to float face down unless the head was constrained to a more vertical position. This configuration also had the highest natural period and the lowest damping of any of the dummy variants.



**Fig. 23.** The Sonoform military PFD (I) on the 50th percentile dummy.

### *PFD G on Human Test Subjects*

The calm water flotation characteristics of freeboard and torso angle for PFD G on the human subjects showed similar behavior to the dummy tests, and particularly the *loose joints* dummy configuration for both the inflated and uninflated tests. The static flotation characteristics for Test Subject I were not significantly affected by assuming either a relaxed or a rigid body posture. Test Subject 2 has a much lower freeboard, which was probably due to a more upright position. While torso angle was not measured on Test Subject 2, the larger faceplane angle indicates that the body as a whole was probably in a more vertical position.

The range of natural periods and damping factors (Figs. 19c and 20c) for both test subjects was generally similar to the dummy tests\*. However, the effects of body postures (relaxed, rigid and help position) on the natural periods and damping factors were significant. Particularly, for the relaxed body posture, where the heave periods were longer and the damping factors higher than in the rigid body case.

Observations noted during these tests (and observed in the data) were that the test subjects could affect the results with only slight changes in body movement. A slightly arched back or bending of the knees, and even (for Test Subject 2) allowing the head to tip further back (by relaxing the neck) greatly increased the damping (reference run 128). Still, the agreement with the *loose joints* dummy was quite good in the static flotation case, and the oscillation results for Test Subject 1 in the rigid body posture, were nearly identical. This suggests that in future dummy designs, the joint stiffness must be decreased, and also, that in theoretical comparisons, a rigid body assumption will slightly under-predict the natural heave period, and significantly under-predict the damping. Figure 24 shows Test Subject 1 wearing the inflated PFD (G) during calm water flotation tests.

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\* with the exception of the uninflated PFD, in relaxed body position.



Fig. 24. Test Subject 1, wearing PFD (G), during flotation experiments.

## Frequency Response

Figures 25 through 28 are presented to illustrate the frequency dependence of the uncoupled heave response for various PFD's and body types. These results are based on the calculation methods presented in the background section of this report and the data presented in Table 5(a).

In Fig. 25a the magnification factor is presented for PFD (A) versus the ratio of natural frequency to wave frequency, calculated by both methods described earlier: MF from Eq. 11, and  $x/r$  (or MF') from Eq. 13. This figure illustrates differences in applying the two calculation methods. For this example a draft of 1.5 ft (0.5 m) to the vertical center of buoyancy was used in calculating  $x/r$ . The asymptotic behavior of both factors are as they should be, in that at low frequencies they converge toward one, and at high frequencies toward zero. Very low frequency response can be thought of as the body *contouring*, or perfectly following the slow change in the water level (such as a response to a change in *tide*). Response in high frequency waves can be thought of as in *ripples* not having enough energy to excite the body into motion. The  $x/r$  curve in Fig. 25a provides a better indication of what the motions would be like, and for PFD (A), this figure shows a response amplitude in heave to be roughly 1.5 times the wave amplitude at the natural frequency of 1.6 seconds (at  $\omega/\omega_n = 1$ ). Figure 25(b) presents the corresponding phase angle comparisons, where *sigma* ( $\sigma$ ) is from Eq. 12 and *total phase* from Eq. 15 ( $\sigma'$ ). Note that motions become 90 degrees out of phase with the wave at the natural frequency (as expected).

The sensitivity of the magnification factor,  $x/r$ , to the approximation of *draft* is illustrated in Fig. 26. Since the range of  $x/r$  doubles at the peak for an increase in draft from 0.5 ft to 2 ft (0.2-0.6 m), utilizing Berteaux's calculation method will require a better understanding of how to calculate draft for a body. This type of verification could possibly be done by performing a regular wave test on the dummy and comparing the response curves. The effects of body angle on reducing or increasing the effective draft might also be thought of in terms of Fig. 26, in that a body closer to the surface is more subject to the wave excitation than if in an upright position (since orbital wave particle trajectories are greater at the surface).

The effect of body weight (or mass) on motion response is illustrated in Fig. 27 for a  $\pm 30$  percent weight change on PFD (A). Note that as in the case of draft, the variation is greatest at the natural frequency.

Sample calculations were performed to compare the response of a survival suit and PFD (G), inflated on the 50th percentile dummy. Since no complete oscillations were obtained on tests of the survival suit, the damping factor was assumed to be approximately 75 percent of critical for the purpose of illustration, and the corresponding damped natural period was 1.4 sec. Added mass was assumed to equal mass, and calculations of the frequency response were compared using both methods,  $x/r$  and MF, shown in Fig. 28a, and corresponding phase plots in Fig. 28b. This illustration shows how the survival suit contours waves at all but the highest wave frequencies (where there is very little wave energy), since  $x/r$  is never greater than one and the total phase plot shows that it remains in-phase over most of the range (ie. close to zero at low frequencies). The response for PFD (G) shows an increase in the magnification factor and phase angle between 3 and 4 radians/sec or wave periods from 2.1 to 1.6 seconds (corresponding to the natural heave period). This means that a 50th percentile male wearing the PFD (G) in a 2.0 second period wave would be expected to be heaving at a greater amplitude than the wave, and be out-of-phase with the wave, as well (increasing the likelihood of mouth immersions). This *frequency dependence* is the main reason why any PFD wave testing (subjective or otherwise) ought to be conducted in a range of wave conditions.

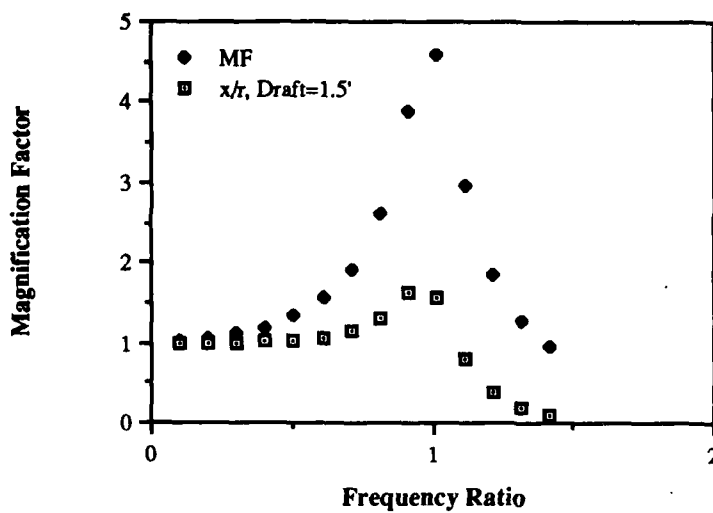


Fig. 25a. Comparison of magnification factors, MF and  $x/r$  from Eqs. 11 and 13, respectively.

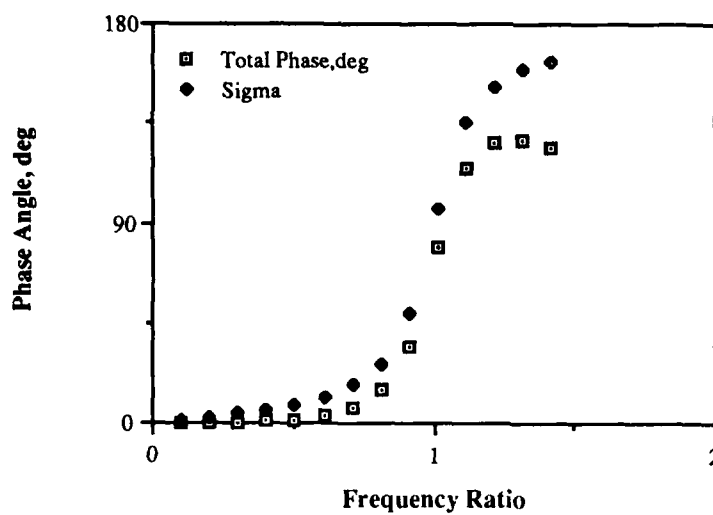


Fig. 25b. Comparison of phase angles, sigma ( $\sigma$ ) and total phase ( $\sigma'$ ) from Eqs. 12 and 15, respectively.

Fig. 25. Comparison of magnification factors and phase angles for PFD (A), calculated using the two methods presented.

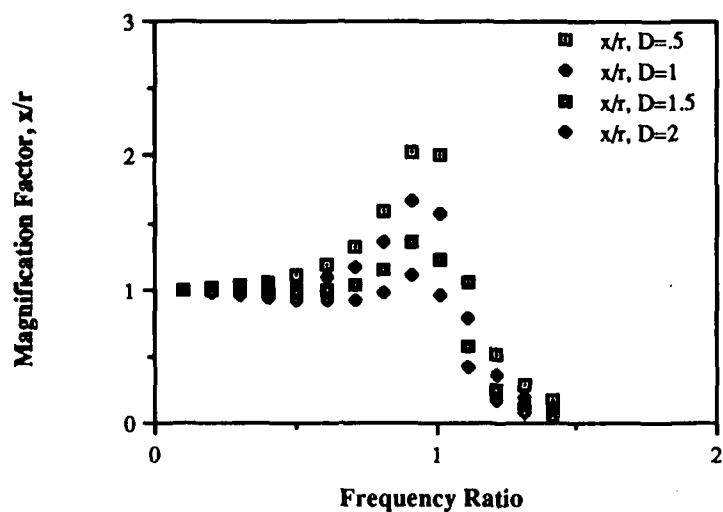


Fig. 26. Effects of Draft , D, on the magnification factor, MF, for PFD (A).

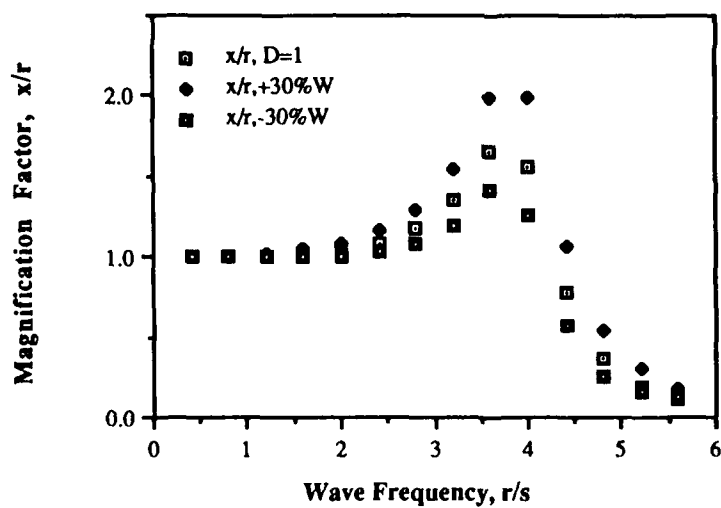


Fig. 27. Effects of a  $\pm 30$  percent weight variation on the magnification factor, MF, for PFD (A).



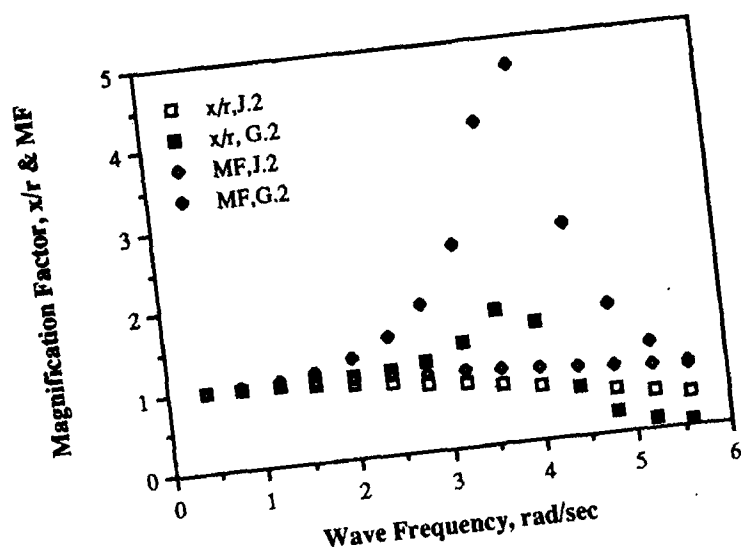


Fig. 28a. Magnification factor comparison.

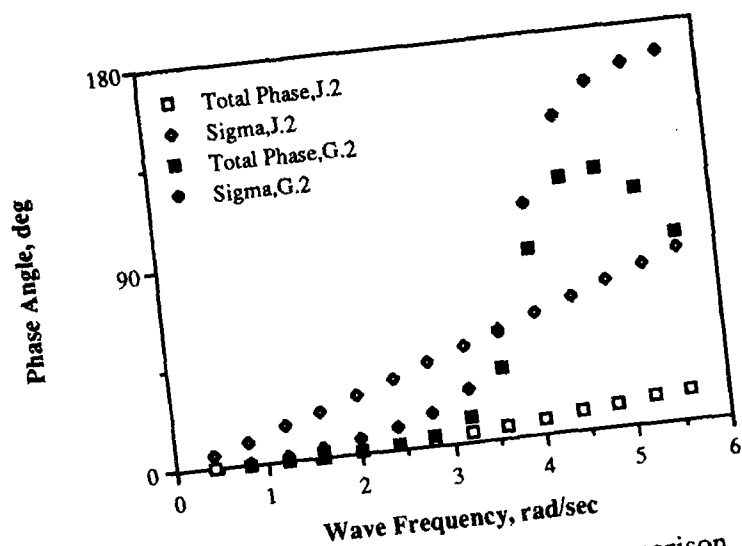


Fig. 28b. Phase angle comparison.

Fig. 28. Comparison of the magnification factors and phase angles, for the survival suit, PFD (J), and the hybrid PFD (G).

## PFD WAVE EXPERIMENTS

Four previously conducted *qualitative* PFD waves experiments were reviewed in light of the range of measured natural heave frequencies (between 1.4 and 3.5 seconds), and the frequency dependence issue. The four tests, two of which were conducted in the United Kingdom and two in the United States, were conducted in *regular* (periodic) waves using human test subjects to evaluate PFD's. Table 6 summarizes the wave conditions of each.

**Table 6.** Wave conditions on previous rough water PFD tests.

Reference	Location	Wave Height ft. (m)	Wave Period seconds	Wave Steepness height/wavelength
1. Girton & Wehr [Ref. 1]	DTRC, U.S.A.	3.8' (1.2m)	2.5	1/17 - 1/8.5
2. Geartest, LTD [Ref. 28]	U.K.	2.3' (.7m)	2.25	1/11
3. R.G.I.T. [Ref. 32]	U.K.	3.3' (1m)	3.75	1/22
4. Wyle Labs [footnote, p.18 &75]	University of Michigan, U.S.A.	.25, .5, 1' (.08, .15, .31)	.8, 1.5, 2.0	1/13, 1/23, 1/20.5

A review of the accounts of each test suggests that the observed performance may have been strongly influenced by the specific wave conditions used to model *rough water* (particularly the wave frequency in relation to the possible natural frequencies of the tested devices and subjects). Tests conducted by Girton and Wehr<sup>1</sup> and Geartest<sup>28</sup> provided similar accounts of the test subjects' response to the waves. Both indicated that these were severe waves and in both cases the wave frequency used (2.25, 2.5 seconds) may have been right in the middle of the range of PFD/subject natural heave frequencies. In the tests at DTRC, Girton and Wehr<sup>1</sup> reported that even with PFD's of 35 lb buoyancy, some people were being submerged occasionally by the waves. Waves in this test were composed of regular waves generated from two perpendicular directions simultaneously (see Fig. 29). Girton and Wehr<sup>1</sup> also reported that although PFD's with 3 in. calm water freeboard generally provided adequate support in

waves, some PFD's with lower calm water freeboards did better. This may have been a case of the PFD providing higher freeboard in calm water was being tested at its natural frequency, making it look worse than other PFD's. Another possibility is that the PFD providing lower freeboard, may have had more *reserve buoyancy*, thus improving the rough water performance.

Tests were conducted by RGIT<sup>32</sup> in waves higher than in the Geartest<sup>28</sup> experiments, and they reported that test subjects handled these waves rather easily (with few wave slaps to face). Using a wave period of 3.75 seconds, these waves were significantly less steep, and also were further from the likely natural frequencies of persons in PFD's. The RGIT tests were conducted with PFD's of generally larger buoyancy, more freeboard and providing more horizontal angle of inclination on the wearer. These PFD's appeared to provide greater waterplane area (higher natural frequency, lower period) and thus the expected motion response would be similar to the survival suit, with a tendency to contour these waves. However, when RGIT repeated the tests out in a real seaway, they reported an increase in wave slaps (to the face of test subjects) which may have been due to the higher frequency components in the random waves at sea.

Tests conducted by Wyle Labs\* at the University of Michigan intended to study the effects of wave frequency and PFD waterplane area on performance by testing several PFD's at three wave conditions. In these tests, observers considered the reported wave slaps to be mere splashes, and of little consequence. This apparently mild motion response may have been due to the wave frequencies being on the high side of the natural frequencies, as well as lower amplitudes (and steepness) used. The wave periods used in these tests were lower than the other tests as were the wave amplitudes. Wyle noted that

*"It had been hoped that the effects of buoyancy and freeboard on the probability of mouth immersion would overshadow the water plane differences from one PFD design to the next. Unfortunately, this was not the case."*

Wyle also went on to recommend the use of a suitable dummy to eliminate the person to person difference in rough water performance studies. These tests identified several areas of improvement in PFD designs,

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\* Wyle Laboratories, "Rough Water PFD Test Letter Report," United States Coast Guard, Sponsor, Contract DOT-CG-831476-A, unpublished.

including wearability and reliability issues. However, because tests were conducted in limited ranges of wave conditions, and the variability of test subject performance was a noted problem, the dynamic performance may not have provided realistic comparisons between the PFD's.



**Fig. 29.** Photograph of waves during rough water PFD tests at DTRC in 1983.

## CONCLUSIONS

Assessing lifejacket performance in rough water is an extremely complex problem and involves many disciplines. This report has addressed the problem by identifying and categorizing the key factors involved in forming an overall problem definition. Also presented are results of experiments designed to explore the analogy of the PFD/Wearer system to rigid body hydrodynamics, and to study the significance of the system's natural heave frequency on motion responses in waves. The following conclusions are given based on the experimental investigations and background studies presented in this report:

1. Conclusions specific to the experimental results are:

- The anthropomorphic dummy used in these experiments provided a consistent basis for quantitative comparison between the various PFD's tested. The correlation between dummy and human response was good, particularly for static flotation. However, the best correlation between the dummy and human response was with the human subject assuming a "rigid body posture." Also noted during these tests (and observed in the data) were that the test subjects could affect the results with only slight changes in body movement. A slightly arched back or bending of the knees, and even (for Test Subject 2) allowing the head to tip further back (by relaxing the neck) greatly increased the damping. Still, the agreement with the *loose joints* dummy was quite good in the static flotation case, and the oscillation results for Test Subject 1, in the rigid body posture, were nearly identical.
- These experiments, while exploratory in nature, demonstrated that the natural periods and damping characteristics of the PFD/Wearer system could be identified from free decaying oscillations in calm water, for specific devices and wearers. The range of natural heave periods for all PFD's tested was between 1.4 and 3.5 seconds. This is significant in that these are the periods most likely to be of interest in waves tests, since rigid body theory would predict that the motions of a person wearing a PFD in these waves would probably be a maximum. Also these wave frequencies are typical of areas such as bays, lakes, large rivers, reservoirs, etc., i.e. where a heavy concentration of boating activity occurs (and most of the accidents).

- Naval architecture prediction techniques appear to be useful within the limitations of the experiment (low amplitude oscillations). Damping characteristics were surprisingly linear and trends in heave natural frequency correlated well with calculated values using rigid body theory calculations, i.e., the natural heave frequency varied with mass and waterplane area as would be expected. In general, using a rigid body assumption in theoretical calculations will slightly under-predict the natural heave period, and significantly under-predict the damping. The experimental results can be used to estimate the increased damping due to body flexibility.

2. In the study of marine accident reports and statistics, several observations and conclusions were made:

- Accident statistics and reports clearly show that the lack of PFD use among recreational boaters is a problem, and that efforts should be continued to improve the wearability of PFD's (through public awareness, and new devices such as hybrids, passive inflation devices, etc.).
- The majority of reported fatalities occur in relatively calm, non-tidal waters such as lakes, ponds, reservoirs, rivers, etc., without the aid of a PFD. Therefore, the types of waves occurring in these regions are of significant interest in PFD studies.
- Reports show that flotation assistance of any kind can significantly improve one's chance of survival, even in extremely rough water.
- The annual presentation of boating accident statistics is not adequate to evaluate the current state of rough water performance problems, since no cross-correlation is provided between the various categories of fatalities; by PFD usage, the body of water, the roughness of the water, and the specific cause of the accident.

For more details on how accident statistics should be used to better define the occurrence and context of rough water performance problems, see pages 9 and 23.

3. An anthropomorphic dummy has been demonstrated to provide a good representation of a human in quantitative PFD performance experiments (DTRC and others). Anthropomorphic dummies have several advantages over human test subjects in quantitative PFD experiments:

- They can be instrumented internally to measure the sensitive parameters involved in flotation experiments.
- They provide a good repeatable base (or control element) in quantitative tests, since they eliminate the subjective variations that often occur when using human test subjects. Therefore, comparisons between specific PFD's might better reveal the quantitative factors that most significantly impacts PFD performance.
- Unlike human test subjects, dummies can remain in the water indefinitely, thereby increasing the efficiency (time and cost) and safety of experiments. See pages 21 and 63 for more detail.

4. Detailed anthropomorphic data are required in the study of human dynamic performance. While height and weight data are readily available, engineering properties such as *distribution* of body mass and buoyancy are also required (and less readily available). These types of data are needed for:

- determining a person's buoyancy requirement
- generalizing the characteristics of various population groups as percentile distributions
- the selection and design of anthropomorphic flotation dummies
- the selection of test subjects for PFD experiments
- the development of theoretical computer models.

Several sources of these types of data are presented in this report, with examples of current applications in biodynamics.

5. In the area of simulation and theoretical modeling of the dynamics of PFD's, a sophisticated human body dynamics computer simulation, the Articulated Total Body model (ATB) currently in use by the Air Force, has potential to be developed into a valuable tool for the evaluation of PFD performance. The ATB model incorporates a level of detail not previously approached in past attempts to analytically model the characteristics of a person in a PFD. This program could be developed to simulate and study the static flotation performance of various PFD's on different human body types. Since the calm water flotation performance is still the main criteria for evaluation and approval of new PFD's, such modeling has long

term potential for use as a cost effective and quantitative PFD design and evaluation tool. Specific recommendations are given in the next section regarding this program.

## RECOMMENDATIONS

Several areas of research will need to be continued to develop practical methods of evaluating the rough water effectiveness of various PFD designs. These areas include; improvements in the analysis of accident data to identify and define problem areas, the development and application of biodynamic math models, and improved experimental techniques used in the studies of biodynamics and hydrodynamics, to meet near term as well as long term goals in PFD research. The following specific recommendations are based on both short and long term goals and are presented as practical applications of the research presented in this report:

1. The analysis and presentation of the Boating Accident Report data should be revised to present;
  - the cross correlation between the use of a PFD, and the specific cause of the fatality ; the body of water; and the water roughness at the time of the accident.
  - the ratio of survivors to fatalities for individual accidents, as a function of PFD usage, water roughness and the cause of the accident.

Statistics which characterize this type of information would provide a more accurate perspective on the effects of rough water and other factors on fatalities. This information could be used to design the specific test conditions in future experiments. Also, these statistics might be used in formulating probability indices of survival in rough water for use in the life saving index (LSI) evaluation tool. This study of accident statistics may represent one of the more cost effective actions, since the necessary data are already routinely collected and compiled annually by the USCG.

2. A set of improved anthropomorphic flotation dummies should be designed and acquired for use in:
  - the quantitative standardization of all current PFD performance experiments (for USCG approval)



- future quantitative performance experiments (both calm and rough water)
- tests where human subjects would not be safe
- the development and validation of analytical/theoretical performance prediction tools.

Results of tests presented in this report indicate that improvements in dummy design must be made with regard to joint flexibility and neck stiffness.

3. Available technology in the field of biodynamic computer modeling ought to be utilized to develop analytical and theoretical tools for studying the dynamics of a person wearing a PFD in the water (calm and rough) and the driving factors in system performance. A program such as the ATB has potential to:

- perform detailed calculations which are difficult to measure experimentally,
- model different body characteristics consistently, to study effective performance of various PFD's,
- provide avenues for cooperation between biodynamics experts and hydrodynamicists in developing simulation capabilities.

Specifically, a program such as the ATB should be developed to perform:

- calculations of geometric and inertial PFD and human body properties (waterplane areas, centers of mass and buoyancy, above and below water volumes, reserve buoyancy, etc.),
- calm water flotation equilibrium and stability calculations.

Data from experiments conducted on the Sierra dummy in this project could be used in the development of this type of model.

4. Future PFD wave experiments should be conducted over a range of wave conditions varying in frequency and amplitude. These conditions should encompass the range of natural heave frequencies of typical devices, to account for the frequency dependence of the PFD/Wearer motion response. The natural periods (frequencies) of the devices tested in this project were within the range of waves that can be generated in many large wavemaking facilities.

5. The analogy between rigid body hydrodynamics and human motion responses should be further pursued. Accordingly, study should continue to determine the extent to which existing ship/buoy design practices can reliably be applied to the study of PFD's.

Many other suggestions and recommendations for future work have been mentioned or implied throughout this report and many other areas of research could be derived from suggestions made. While the practical limitations on sponsoring this type of research are recognized, it is hoped that this report provides a logical framework for prioritizing and conducting future PFD performance studies.

### ACKNOWLEDGMENTS

The author wishes to thank the following individuals for their cooperation and assistance in this project:

- Mr. Samuel E. Wehr of the Survival Systems Branch of the USCG, for continued guidance, support, and assistance in finding and providing information, reviewing results, and for participating in experiments.

- Dr. Arnold Higgins of the Federal Aviation Administration's Civil Aeromedical Institute for supplying information on the use of dummies in PFD testing and for providing the use of the Sierra Sam anthropomorphic dummy.

- Dr. Ints Kaleps of Air Force Aerospace Medical Research Laboratory, Mr. John T. McConville of The Anthropometry Research Project, and Dr. Alvah C. Bittner of the Naval Biodynamics Laboratory for their contributions and assistance on the topics of anthropometry and biodynamic computer modeling.

- Dr. David D. Moran, Mr. Michael J. Davis, Mr. John F. Dalzell, and Dr. John F. O'Dea at DTRC for their consultation and feedback on hydrodynamic issues as applied to PFD's.

- Mr. John G. Hoyt and Mr. R. Thomas Waters of DTRC for their valuable suggestions in various aspects of the anthropomorphic dummy experiments.

- Mr. Martin Dipper of DTRC for providing computer support for data acquisition, Mr. Tony Casilla of DTRC for his assistance in performing experiments, and Mr. Marty Monier of DTRC for his machining and refurbishing work on "Sierra Sam."

- Lisa Eynon, and Mrs. Susan A. Hart for their assistance in typing and report preparation.

- Jo Anne E. Lappin of the DTRC Technical Information Center for conducting the extensive background literature search, cited in Appendix A.

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## APPENDIX A. INFORMATION ON LITERATURE SEARCH

Literature Search conducted by DTRC Technical Information Center between April '85 and May '85

### DATABASES SEARCHED:

DTIC - Defense Technical Information Center (\*Proprietary Info)

A. Technical Reports

B. Work Unit Information System (Government funded projects)

C. Independent Research and Development (Nongovernment funded)

NTIS - National Technical Information Service

TIRS - Transportation Information Research Service

OCEAN ABSTRACTS

MEDLINE (73-79)

BIOSIS (81-85), (77-80)

### Key Words:

Personal flotation devices, life jackets, life vests, work vests, sailing vests, exposure suits, survival suits, life preservers, wet suits, immersion suits, life support systems, survival equipment, human buoyancy, flotation, floating bodies, drowning, hypothermia, anthropomorphic dummies, mannequins, anthropometric data.

[illegible]



## APPENDIX B. DESCRIPTION OF PFD TYPES

### Off-Shore Lifejacket -- TYPE I PFD\*

- Turns most unconscious wearers face-up in water.
- Most effective type in rough water.
- Reversible; can be put on inside out.
- Two Sizes to fit most children and adults.

#### Intended Uses

- Best for all waters; open ocean, rough seas, or remote water; where rescue may be slow coming.
- Abandon-ship lifejacket for commercial vessels.

#### Advantages

- Best performing PFD of all types in both rough and calm waters.
- Provides best chance of survival for unconscious wearer.
- Best device for nonswimmers if they will wear it.

#### Disadvantages

- Bulky.
- May be too uncomfortable to wear for extended periods.
- May not fit extremes of some sizes well (especially children).

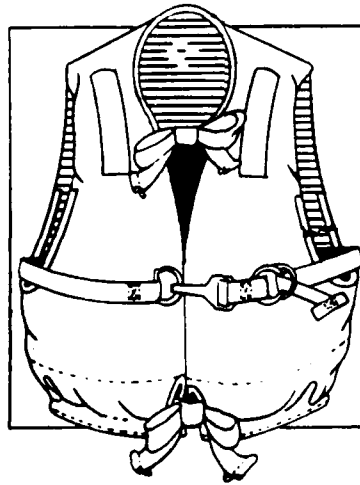


Fig. B-1. Sketch of typical TYPE I PFD.

\* Adapted from a proposed revision of the Standard for Marine Buoyant Devices, UL-1123, prepared by Underwriters Laboratories Inc. for the USCG to be used in consumer information pamphlets. These pamphlets are to be packaged with all (USCG approved) marine buoyant devices (PFD's) sold in the U.S.

## Near-Shore Buoyant Vest -- TYPE II PFD

- Will turn many unconscious wearers face-up in water.
- Sizes: Infant, Child-Small, Child-Medium, and Adult.
- Compromise between Type I PFD performance and wearer comfort.

### Intended Uses

- General boating activities.
- Good for calm, inland water, or where there is a good chance of fast rescue.

### Advantages

- More comfortable to wear than a Type I PFD.
- Keeps most unconscious wearers face-up in water.

### Disadvantages

- May be uncomfortable after wearing for extended periods.
- Will not turn as many people face-up as a Type I PFD will.
- In rough water, a wearer's face may often be covered by waves.
- Not for extended survival in rough water.

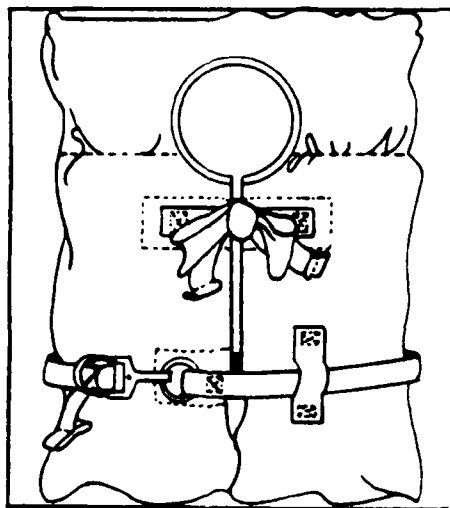


Fig. B-2. Sketch of typical TYPE II PFD.

## Flotation Aid -- TYPE III PFD

- Designed to provide a stable face-up position in calm water for a wearer floating with head tilted back.
- Available in a wide variety of styles, some designed for specific activities.
- Available in many sized for good fit on a wide variety of chest sizes and weights.

### Intended Uses

- General boating or specialized activities including water sports such as skiing, hunting, fishing, canoeing, kayaking, an others.
- Good for calm, inland waters, or where there is a good chance for fast rescue.
- Intended to be matched to your boating activities so that you can wear it.

### Advantages

- Should be comfortable enough to wear for extended periods.
- Designs for a wide variety of specialized boating activities.

### Disadvantages

- Wearer may have to tilt head back to avoid going face-down.
- Will not hold the face of an unconscious wearer clear of the water.
- In rough water, a wearer's face may often be covered by waves.
- Not for extended survival in rough water.

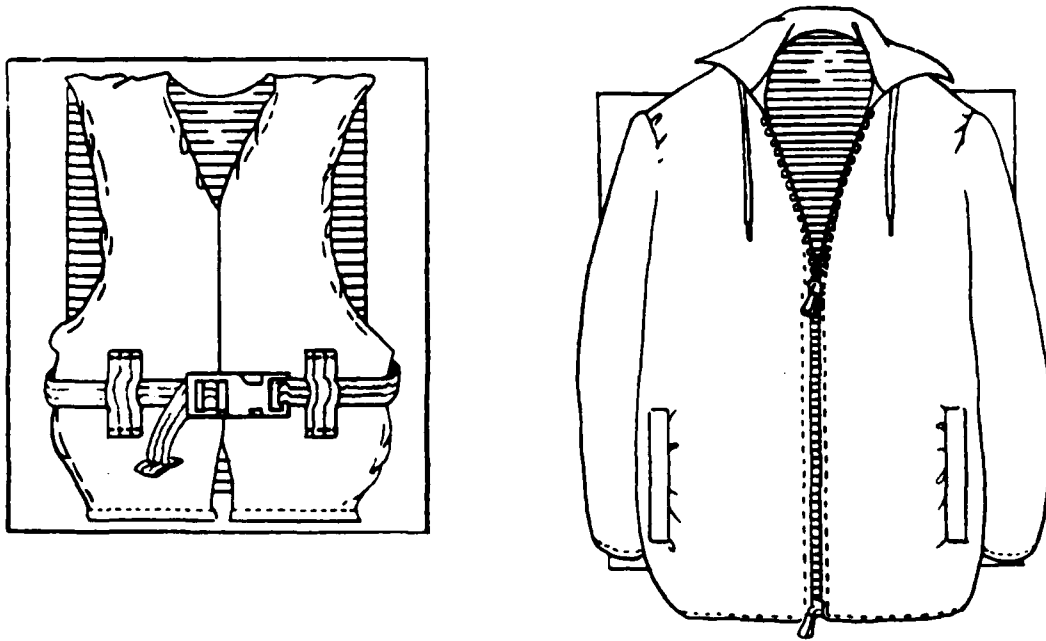


Fig. B-3. Sketch of typical TYPE III PFDs.

### Throwable Device -- TYPE IV PFD

- Designed to be grasped and held by the user until rescued.
- Provides enough buoyancy for users to hold their heads out of the water.

#### Intended Uses

- For use on small boats in calm, inland water with heavy boat traffic, where help is always nearby.
- For use on larger boats as an extra device to aid persons who have fallen overboard. May be used with a lanyard, "man-overboard" pole, locator light, or smoke signal.

#### Advantages

- Can be thrown to someone within 40 feet.
- Can be used as a seat cushion, or some types can be placed in a bracket mounted above deck, where they are immediately available.
- Good back-up buoyancy for use with a wearable PFD.

#### Disadvantages

- Not for an unconscious or exhausted person.
- Not for non-swimmers or children.
- Not for rough water survival.

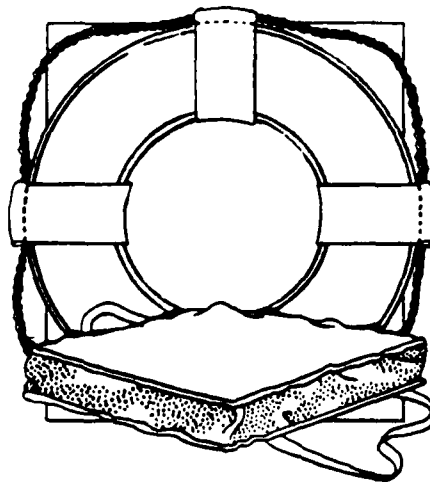


Fig. B-4. Sketch of typical TYPE IV PFDs.

### Special Use Device -- TYPE V PFD

Only for special uses. See label for limits of use. Types include deck-suits, boardsailing vests, work vests, hybrid PFDs which use foam flotation material and an inflatable chamber, and others.

#### Advantages

- Made for specific activities.

## **APPENDIX C**

### **WATERPLANE AREA CALCULATIONS\***

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\* The waterplane area cross-sections are shown as shaded areas superimposed on a rough line sketch of the PFD. The line sketches are not necessarily drawn in the same plane as the cross-section, but are intended to provide perspective on the relative size of the waterplane area to the PFD.

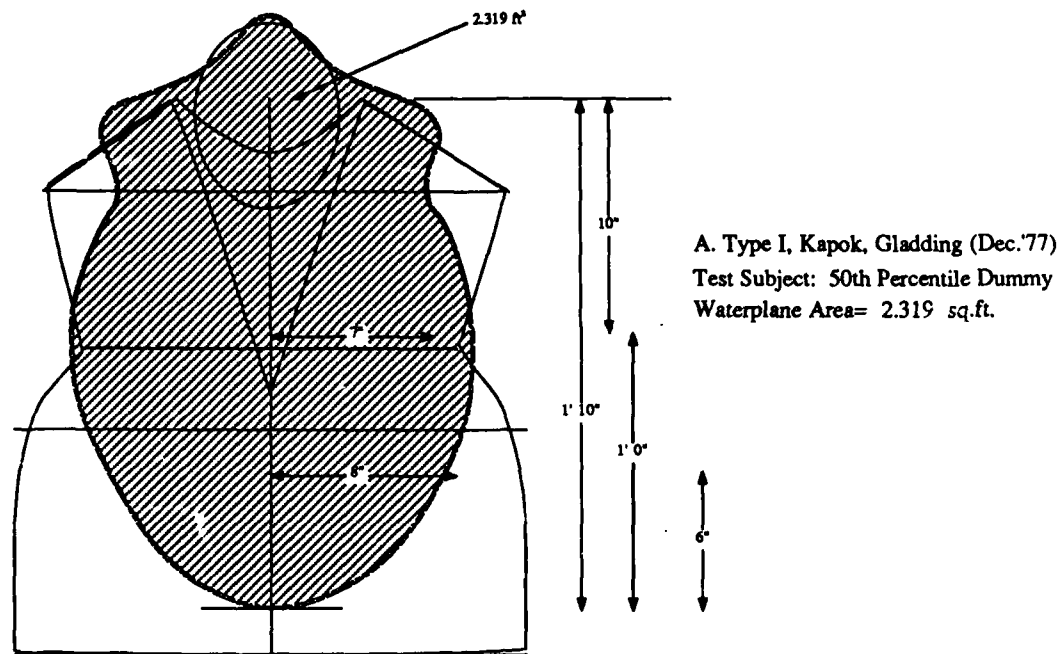


Fig. C-1. Waterplane area of PFD A on 50th percentile dummy.

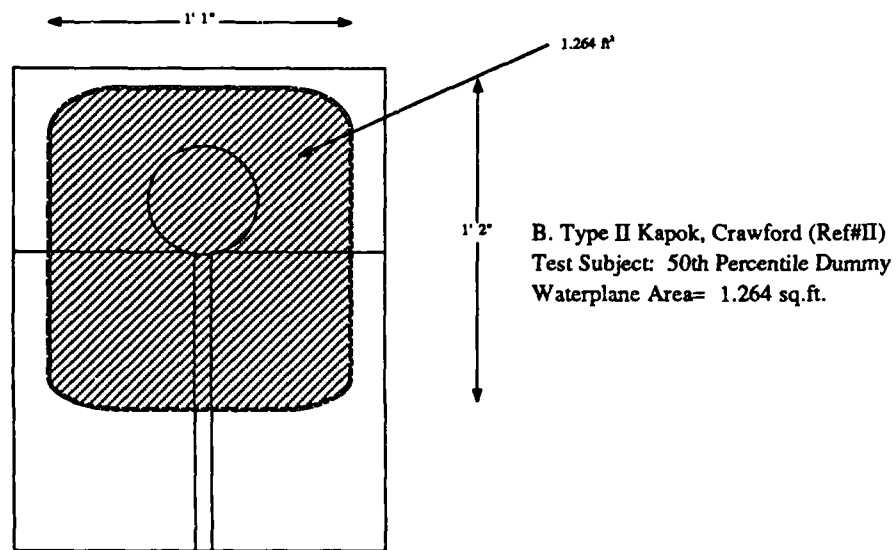
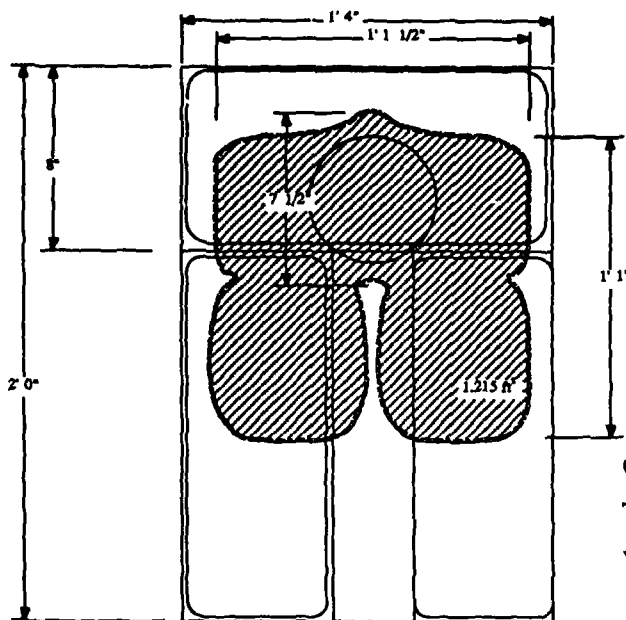
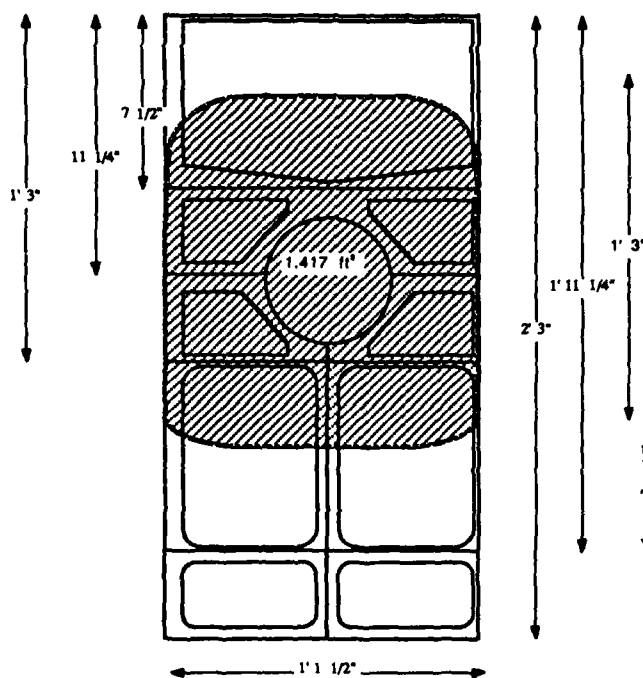


Fig. C-2. Waterplane area of PFD B on 50th percentile dummy.



C. Reference Sample #2 for Hybrids  
Test Subject: 50th Percentile Dummy  
Waterplane Area= 1.215 sq.ft.

Fig. C-3. Waterplane area of PFD C on 50th percentile dummy.



D. Type V, R. Perry  
Test Subject: 50th Percentile Dummy  
Waterplane Area= 1.417 sq.ft.

Fig. C-4. Waterplane area of PFD D on 50th percentile dummy.

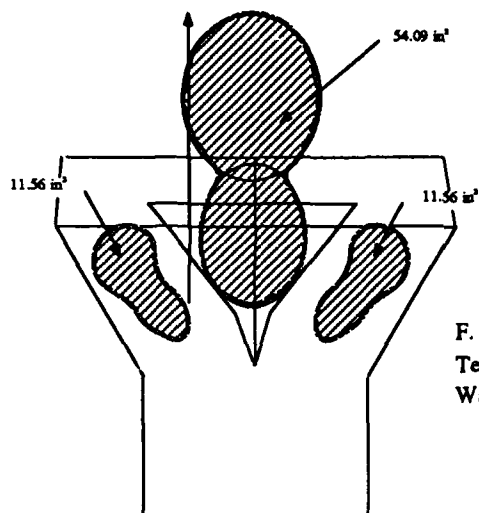


Fig. C-5. Waterplane area of PFD F (uninflated) on 50th percentile dummy.

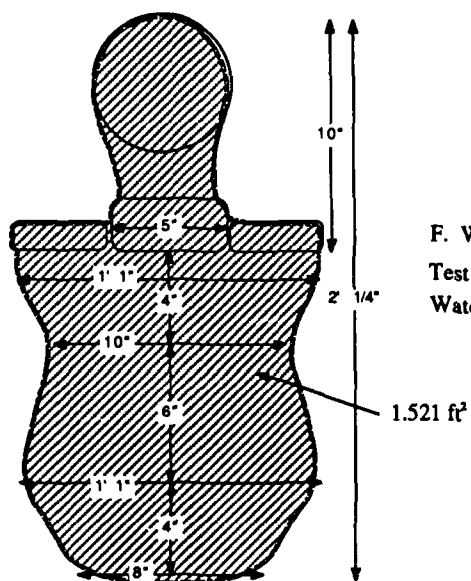
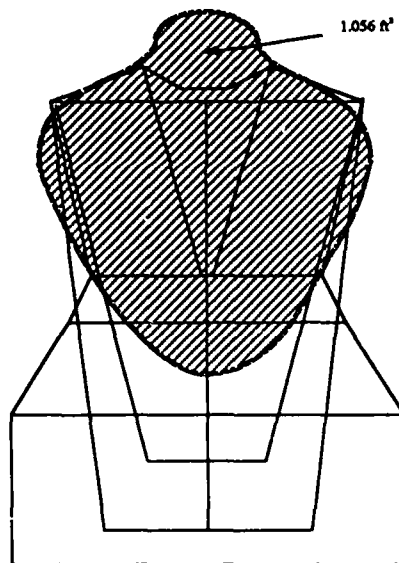


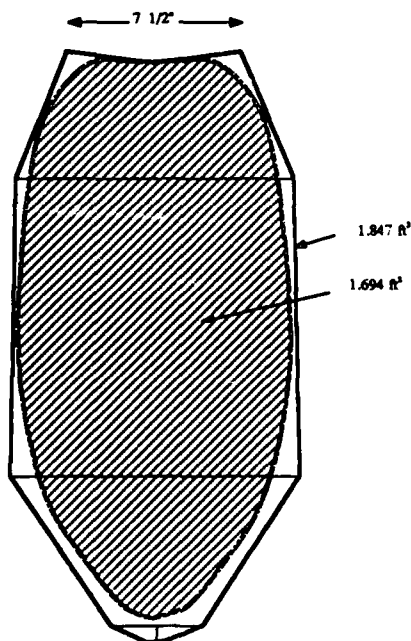
Fig. C-6. Waterplane area of PFD F (inflated) on 50th percentile dummy.





G. Hybrid Helmsman/ERO , Uninflated  
 Test Subject: 50th Percentile Dummy  
 Waterplane Area= 1.056 sq.ft.

Fig. C-7. Waterplane area of PFD G (uninflated) on 50th percentile dummy.



G. Hybrid Helmsman/ERO , Inflated  
 Test Subject: 50th Percentile Dummy  
 Waterplane Area : 1.694 sq.ft.

Fig. C-8. Waterplane area of PFD G (inflated) on 50th percentile dummy.

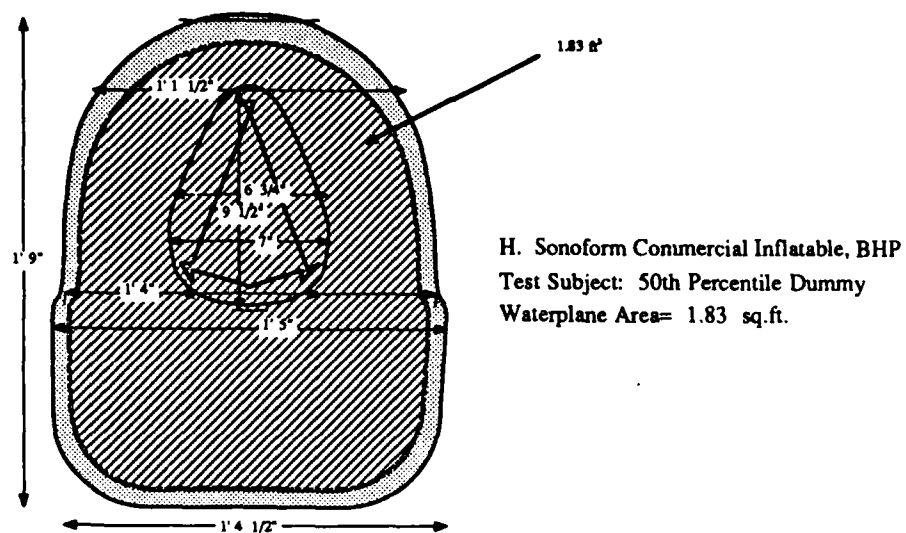


Fig. C-9. Waterplane area of PFD H on 50th percentile dummy.

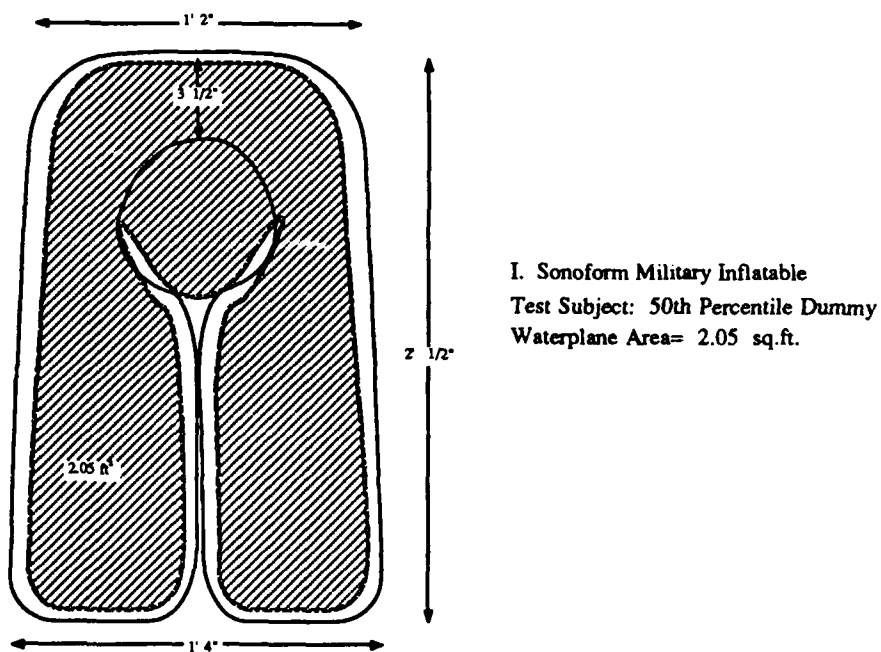
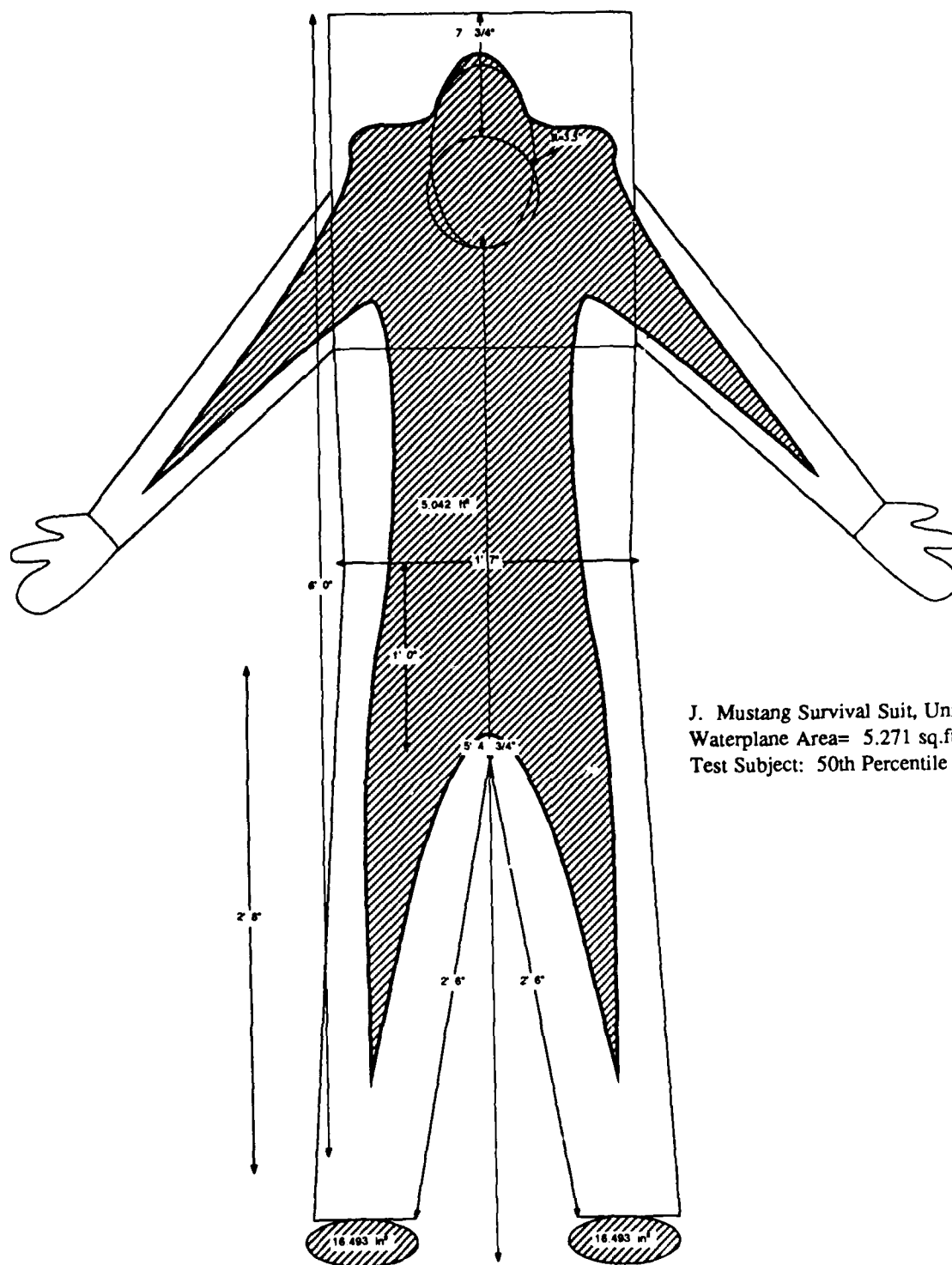
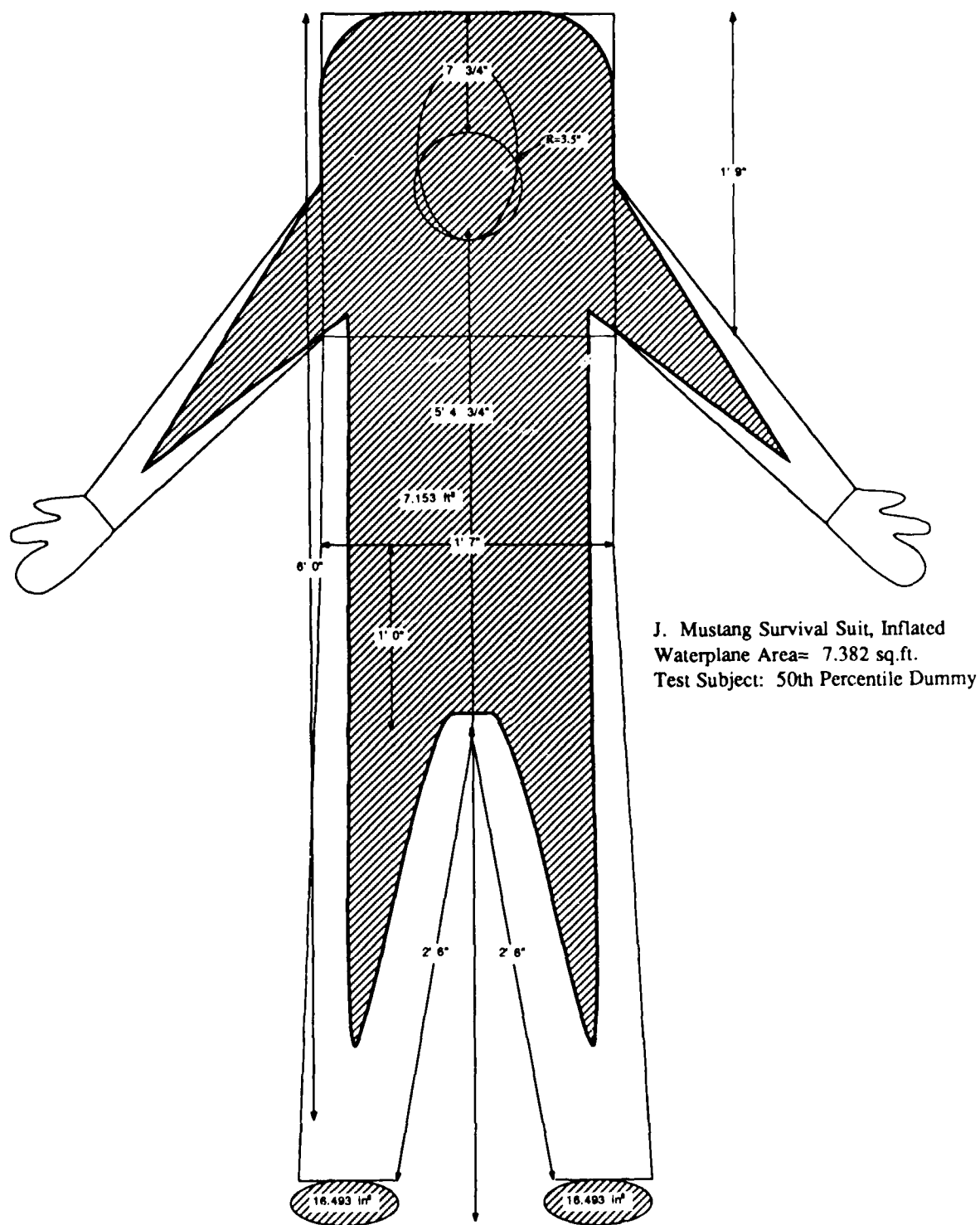


Fig. C-10. Waterplane area of PFD I on 50th percentile dummy.



J. Mustang Survival Suit, Uninflated  
Waterplane Area= 5.271 sq.ft.  
Test Subject: 50th Percentile Dummy

Fig. C-11. Waterplane area of PFD J (uninflated) on 50th percentile dummy.



**Fig. C-12.** Waterplane area of PFD J (inflated) on 50th percentile dummy.

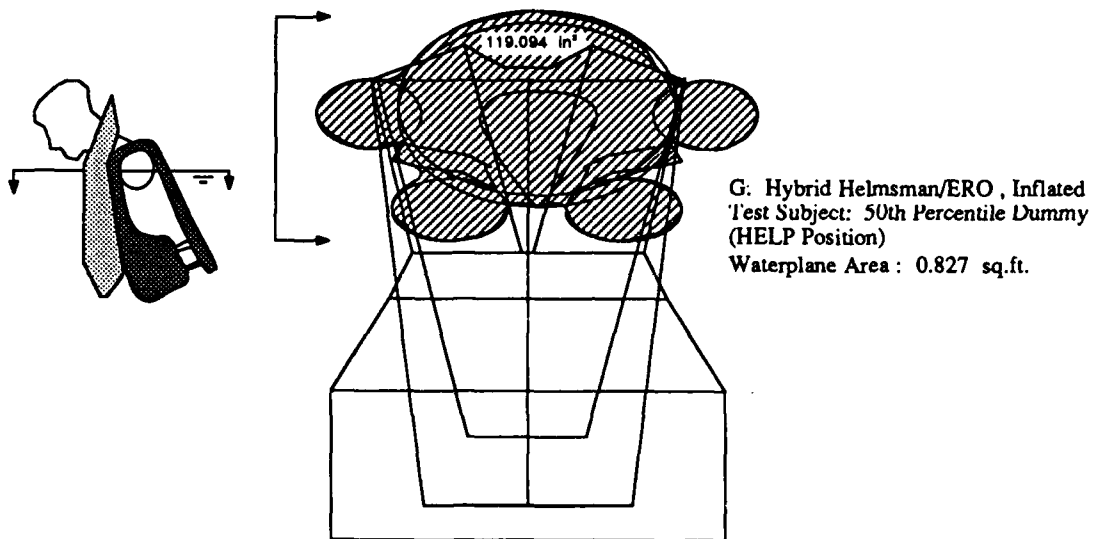


Fig. C-13. Waterplane area of PFD G (inflated) on dummy in HELP position.

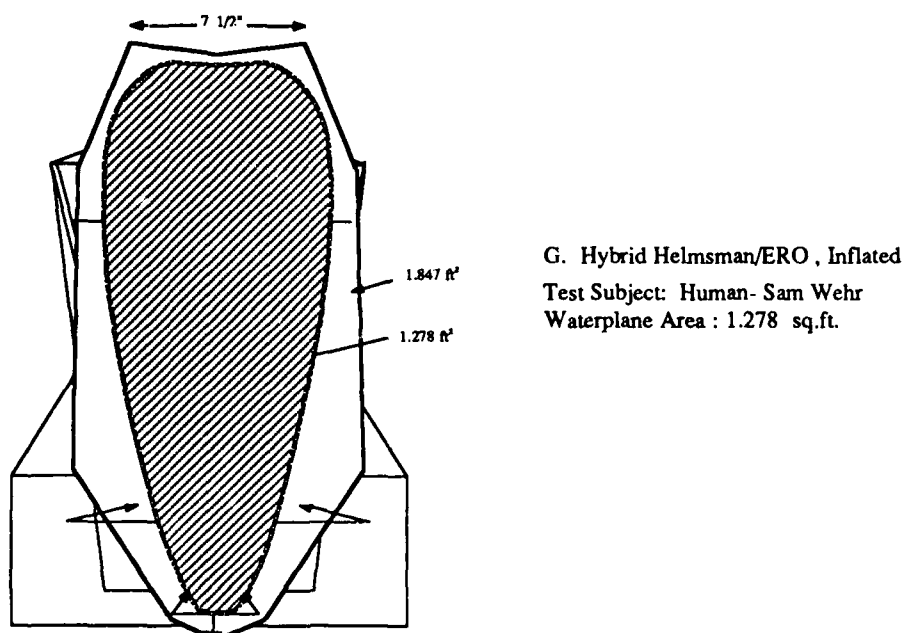


Fig. C-14. Waterplane area of PFD G (inflated) on Test Subject 1.

## APPENDIX D. ACCELEROMETER CALIBRATIONS

Two Systron Donner (Model 4310) linear force balance servo-accelerometers were used to resolve the flotation angle of the anthropomorphic dummy during calm water tests. Accelerometers of this type are generally calibrated by tilting the sensitive axis thru a series of precise angles (using a calibrated tilt table), and comparing the acceleration reading with the corresponding component of gravitational acceleration at each angle. The accelerometers and signal conditioning are designed to output a linear voltage proportional to acceleration in "gs" (where 1 g = gravitational acceleration). The two accelerometers (1g range) were mounted perpendicular to each other, one with the sensitive axis oriented horizontally and the other vertically. *Vertical* accelerometers are designed to compensate for gravitational acceleration by internally subtracting 1.0g from all readings. Therefore, in tilting the sensitive axis of a vertical accelerometer from an upright position to horizontal, the reading moves from zero (1.0g - internal correction) to a reading of negative 1.0g. The corresponding tilt angle can be calculated as a function of the acceleration reading, as follows;

$$\text{Tilt Angle}_{\text{vertical acceleration}} = \cos^{-1} (1 - \text{Acc. in } g' \text{ s}) \quad (\text{D-1})$$

When the horizontal accelerometer is tilted from a vertical to horizontal position, the reading moves from 1g to zero as the inverse sine of the acceleration,

$$\text{Tilt Angle}_{\text{horizontal acceleration}} = \sin^{-1} (\text{Acc. in } g' \text{ s}). \quad (\text{D-2})$$

Figure D-1 shows the linear calibration of volts vs. acceleration in g's for both accelerometers. Figure D-2 shows how the acceleration varies with angle. In this figure the solid lines are the expected curves calculated from Eqs. D-1 and D-2, and the data from the calibration are over plotted with excellent agreement. This figure illustrates why two accelerometers were necessary to resolve the full range of angles. At angles below 20 degrees, the vertical acceleration changes only slightly for a large change in angle, therefore readings from the horizontal accelerometer were used to calculate flotation angle, in this range. Conversely, the horizontal acceleration changes very little for a large change in angle, above 70

degrees, and in this range the vertical accelerometer was used. In the 20 to 70 degree range, the two accelerometer readings were averaged to determine the flotation angle. The flotation angle could therefore be resolved with good accuracy (within 1.5%) and good repeatability .

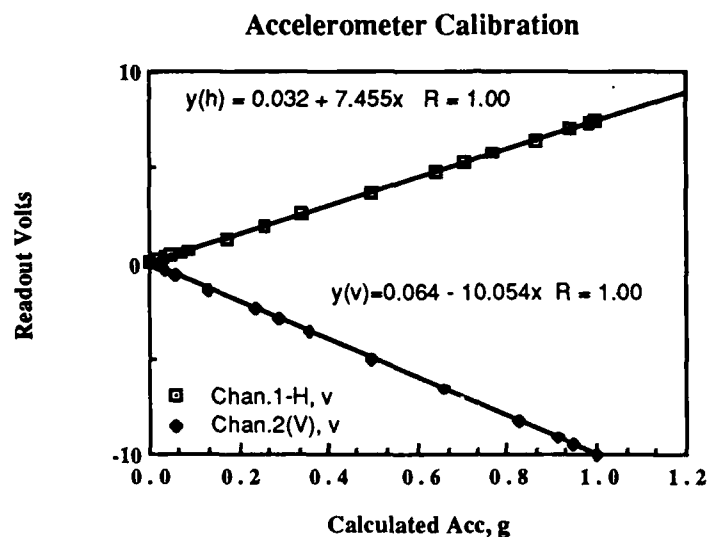


Fig. D-1. Linear calibration of horizontal and vertical accelerometers.

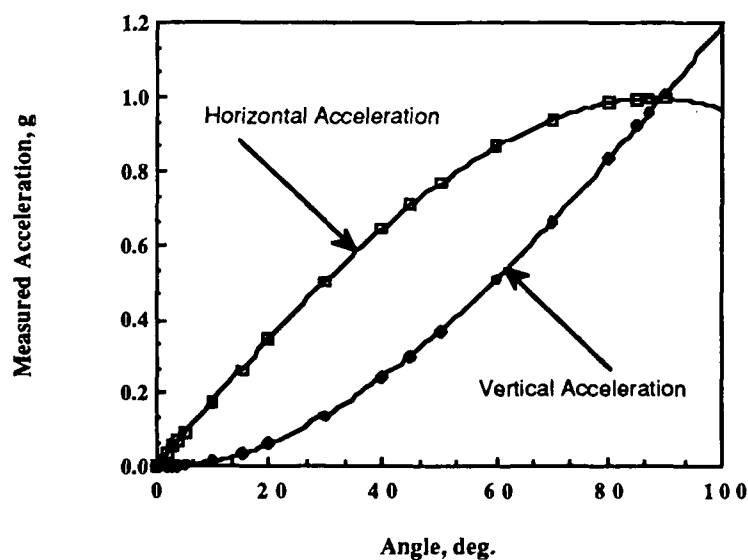
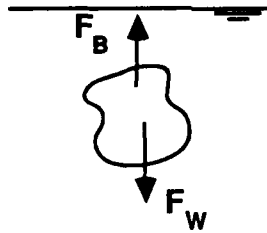


Fig. D-2. Variation of accelerometer readings with tilt angle.

## APPENDIX E. BUOYANCY CALCULATIONS

### BUOYANCY OF A SUBMERGED OBJECT



The total buoyant force,  $F_B$ , on a submerged object due to its displaced volume is given by

$$F_B = \rho_f g V_{\text{body}} \quad , \quad (\text{E-1})$$

and the weight force,  $F_W$ , can be expressed as

$$F_W = \rho_b g V_{\text{body}} \quad . \quad (\text{E-2})$$

The total buoyancy,  $B$ , of a submerged object is then given by

$$B = F_B - F_W = \rho_f g V_{\text{body}} - \rho_b g V_{\text{body}} \quad (\text{E-3})$$

or

$$B = F_B - F_W \left( \frac{\rho_f}{\rho_b} - 1 \right) \quad (\text{E-4})$$

where  $\rho_f$  = fluid density ,  $\rho_b$  = body density, and  $V_{\text{body}}$  = body volume.



## BUOYANCY OF HUMAN BODY

The density of the human body can be determined by knowing a persons' weight in air and in water, as follows:

$$BD = \frac{M_{air}}{\frac{M_{air} - M_{water}}{\rho_{water}} - (V_{lungs} + V_{gas})} \quad (E-5)$$

where  $M_{air, water}$  equals the mass of body in air and in water, respectively, and  $V_{lungs, gas}$  equals the volume of lungs and entrained gas, respectively ( $V_{lungs} \approx 1.35$  liters for men and 1.1 liters for women;  $V_{gas} \approx 0.1$  liters)

The percentage of body fat, %BF, can be calculated from

$$\% BF = \left[ \frac{4.95}{BD} - 4.5 \right] 100 \quad (E-6)$$

where body density, BD, is expressed in kg/liter.

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